Strong-Focusing Cyclotron: FFAG for High Current Applications

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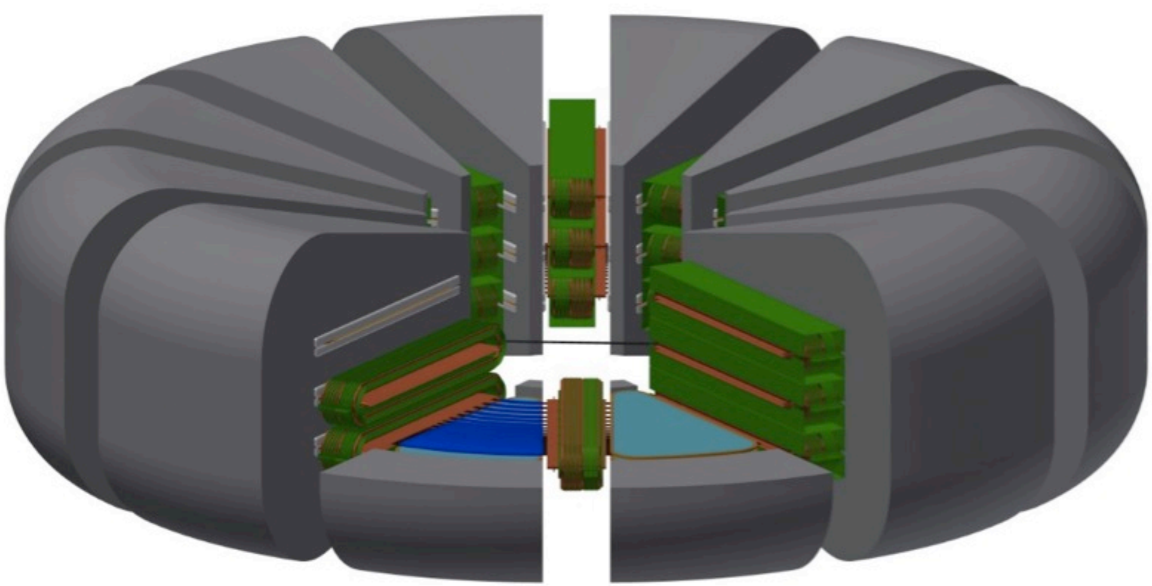

Outline

- Motivation
  - Proton driver for Accelerator-Driven Subcritical Fission
  - What limits beam current in cyclotrons?
- Superconducting RF Cavity
  - Fully separate all orbits
  - Distributed coupling to match beam loading
- Beam Transport Channel
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  - Winding prototype
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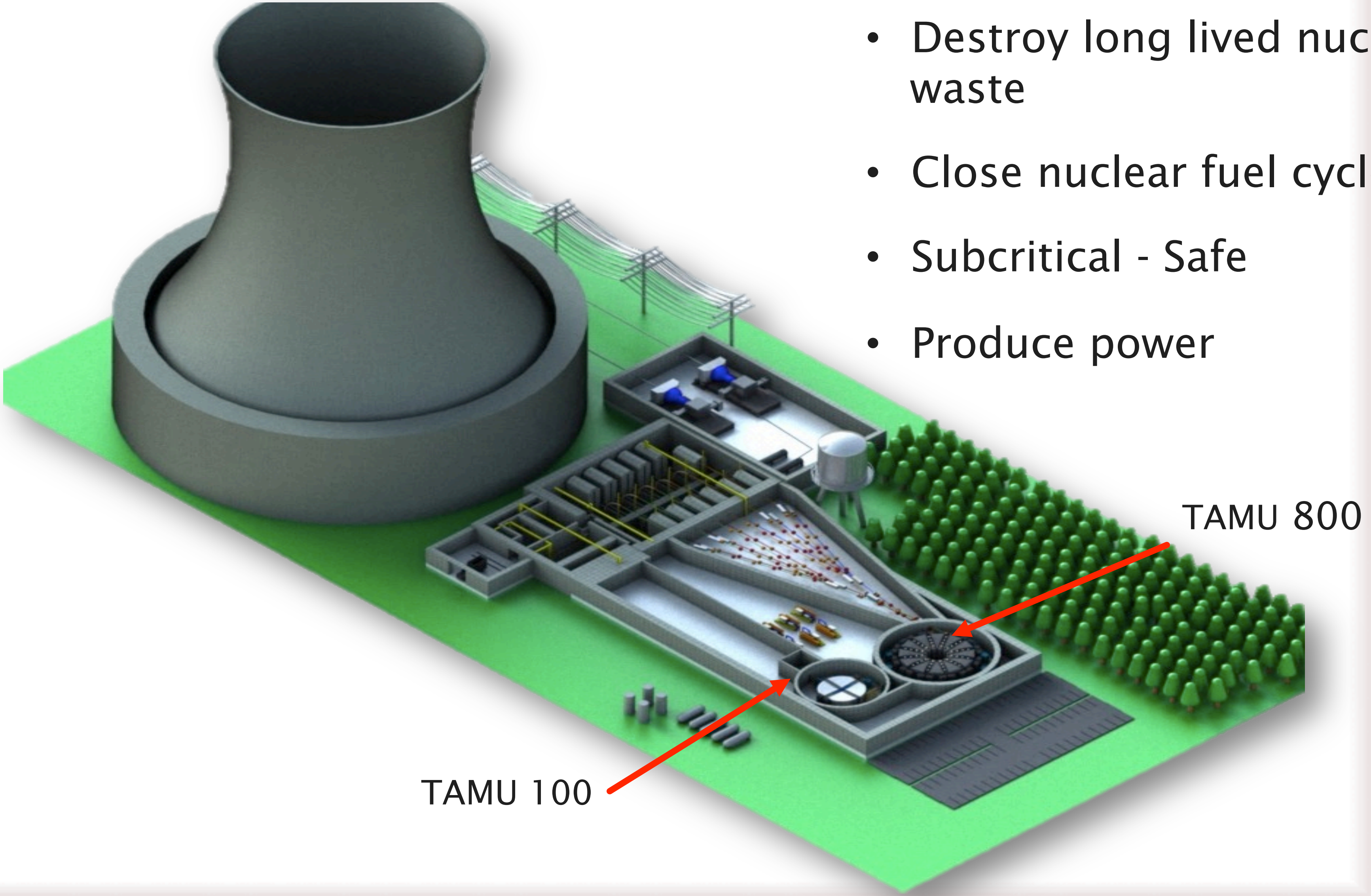
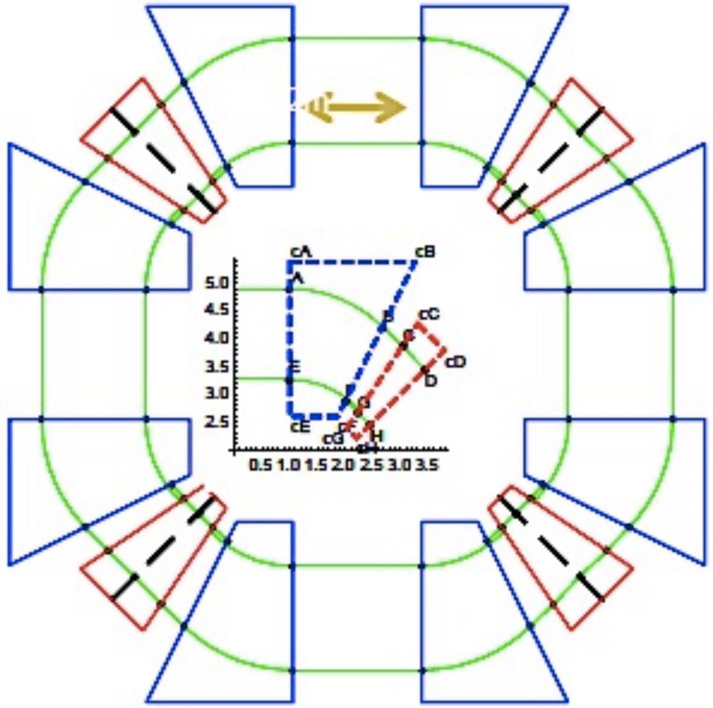
  - Fringe field reduction
- Beam Dynamics

Accelerator Driven Molten Salt System

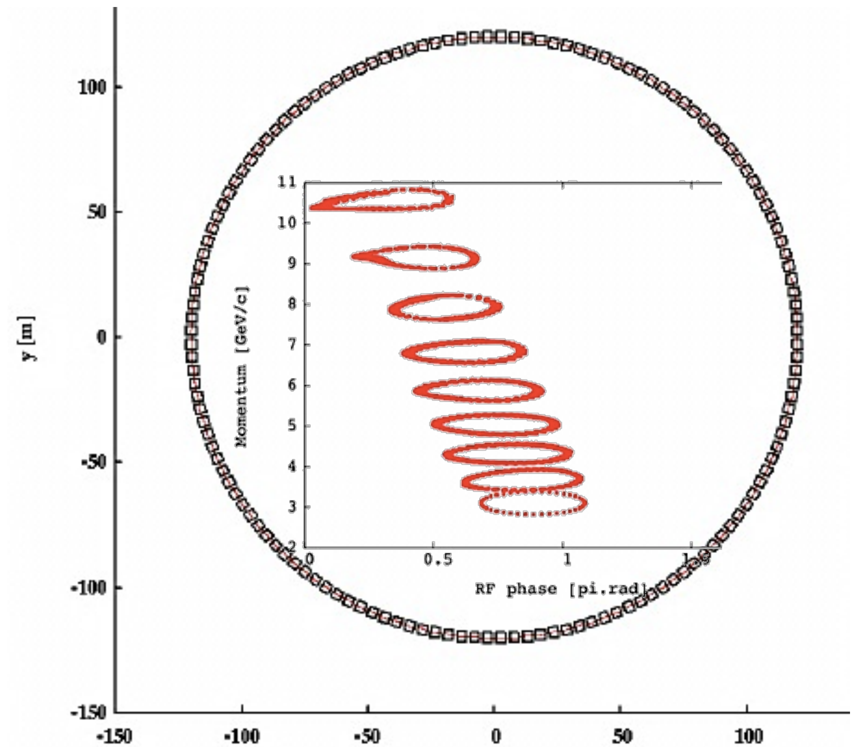


- Destroy long lived nuclear waste
- Close nuclear fuel cycle
- Subcritical - Safe
- Produce power

FFAG is typically configured to accelerate a large momentum admittance within a modest magnet aperture.



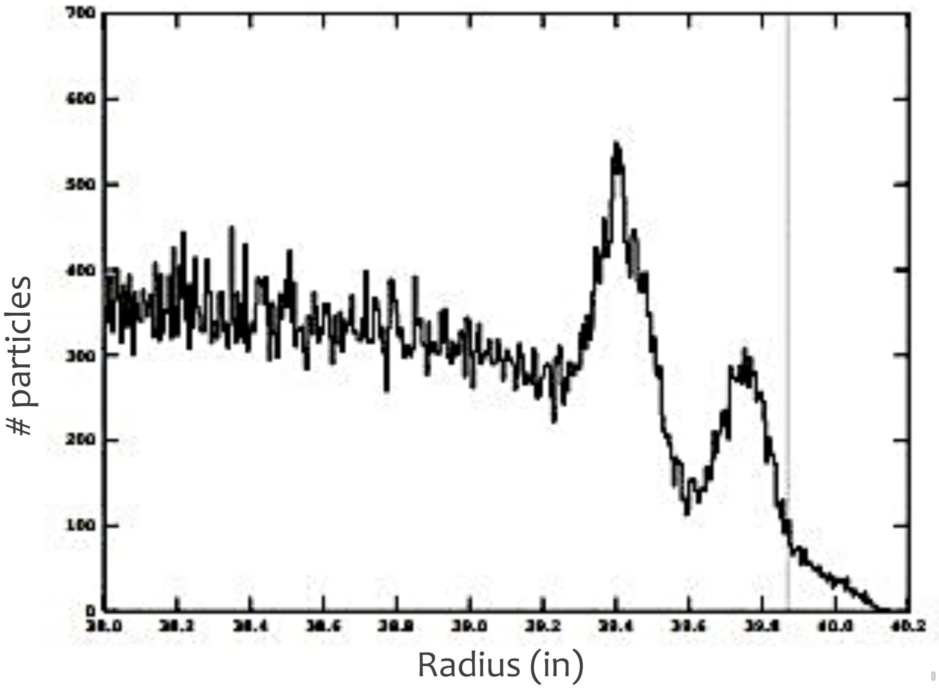
1 GeV CW FFAG for C Therapy
C. Johnstone – Trinity College, 2011



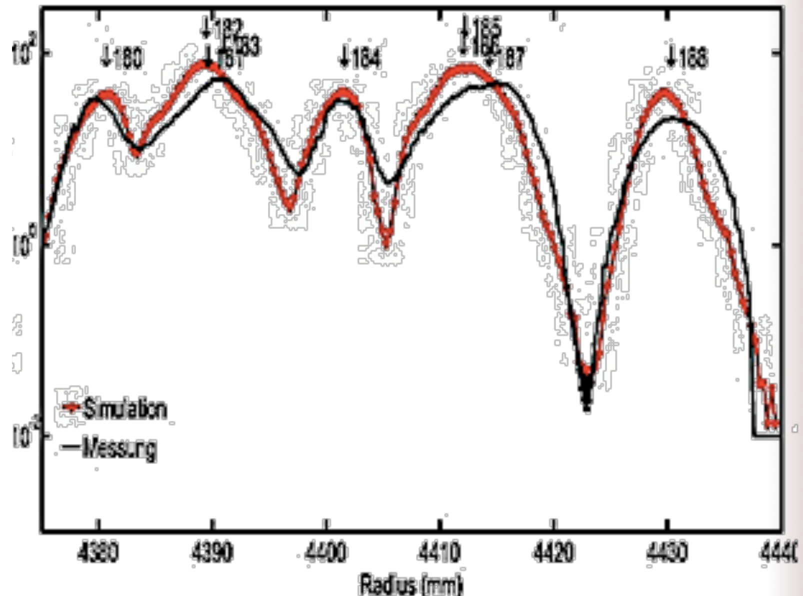
3 to 10 GeV muon double beam FFAG
T. Planche - Nufact09

They are brilliant designs, as long as you don't want too much beam current…

Current limits in cyclotrons:
1) Overlapping bunches in successive orbits



http://www.nscl.msu.edu/~marti/publications/beamdynamics_ganil_98/beamdynamics_final.pdf



http://cas.web.cern.ch/cas/Bilbao-2011/Lectures/Seidel.pdf

Overlap of N bunches on successive orbits produces N x greater space charge tune shift, non-linear effects at edges of overlap.

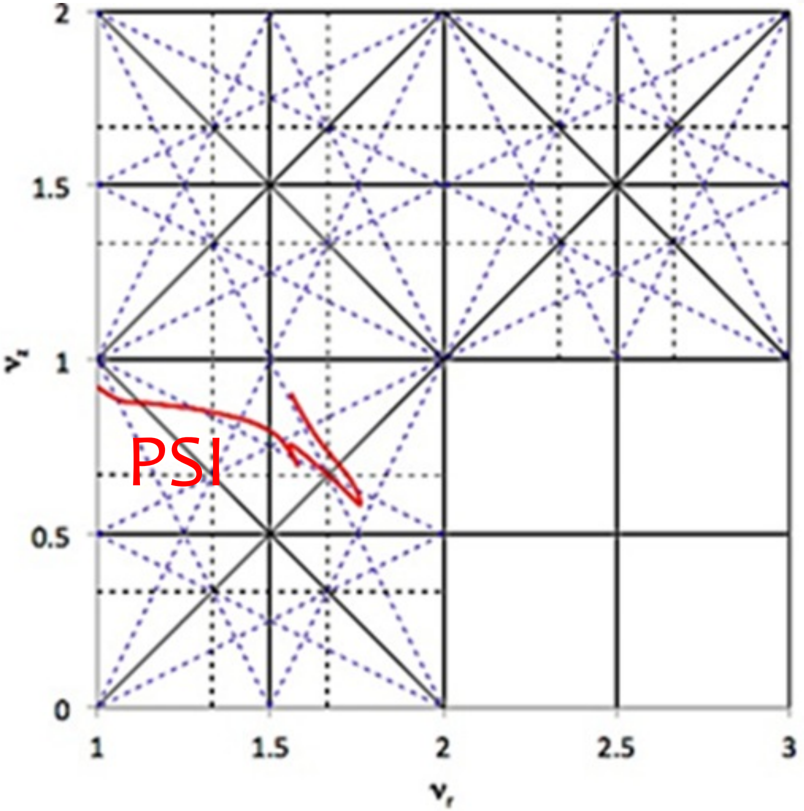
2) Weak focusing, Resonance crossing

Cyclotrons are intrinsically weak-focusing accelerators

- Rely upon fringe fields
- Low tune requires larger aperture
- Tune evolves during acceleration
- Crosses resonances

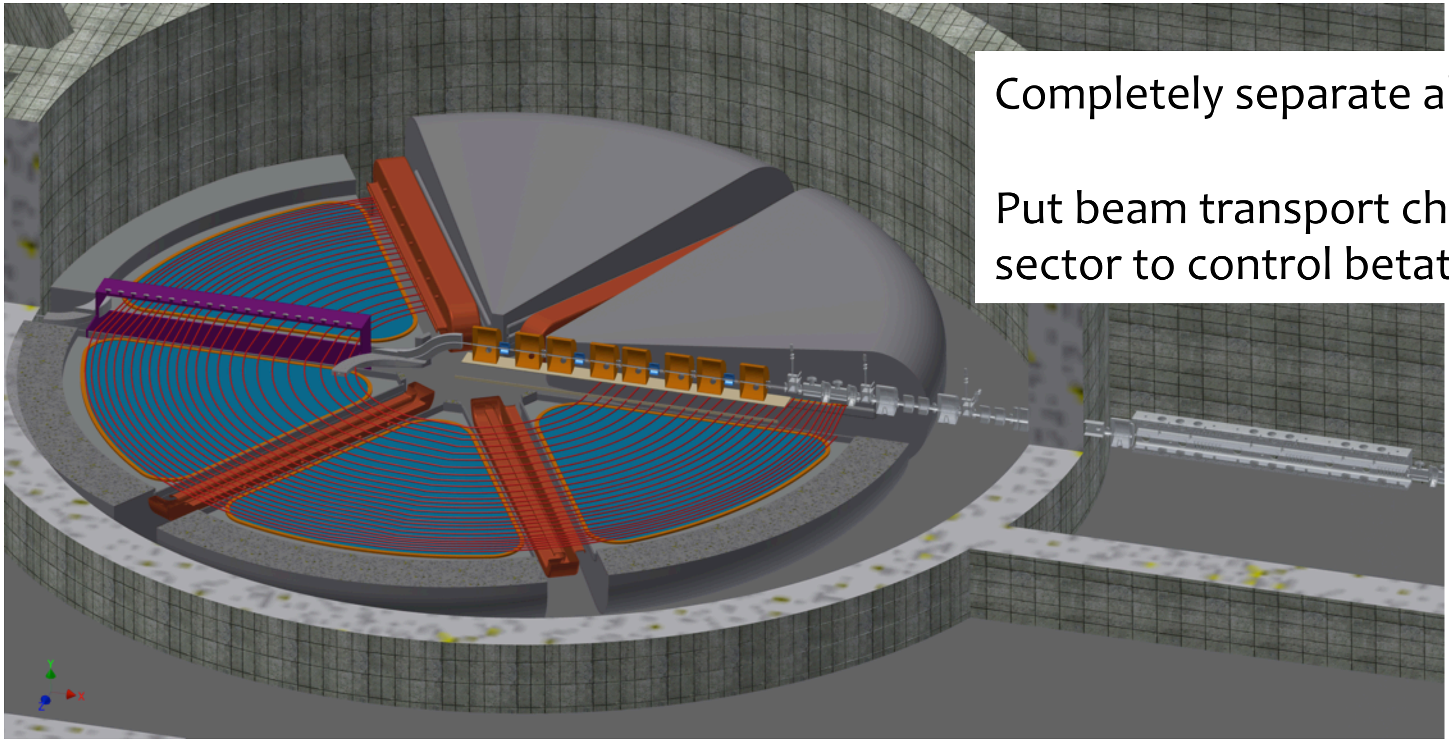
Scaling, Non-scaling FFAG utilize non-linear fields

- Rich spectrum of unstable fixed pts



Space charge shifts, broadens resonances, feeds synchro-betatron
Even if a low-charge bunch accelerates smoothly, a high-charge bunch may undergo breakup even during rapid acceleration

Strong-Focusing Cyclotron



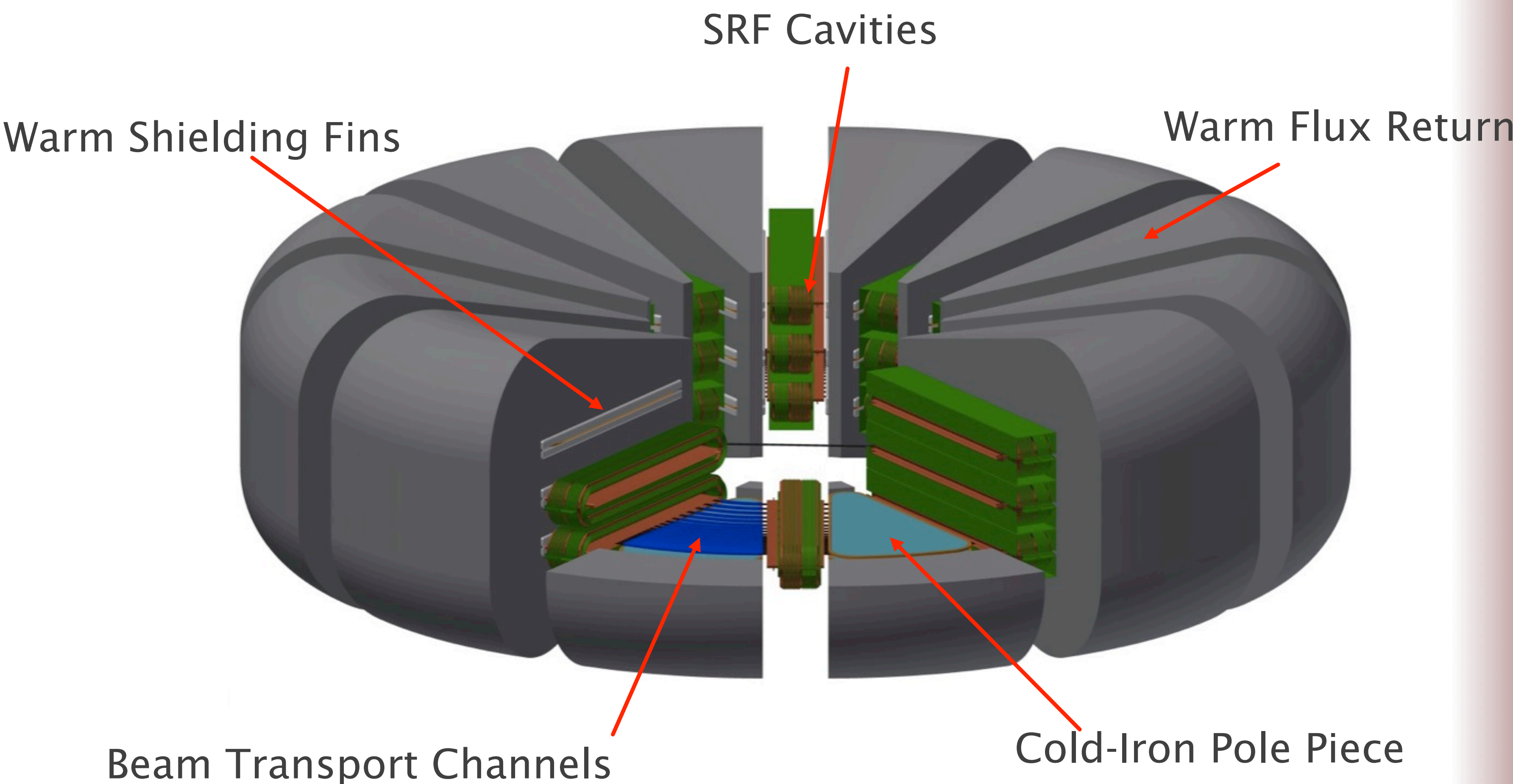
Completely separate all orbits.

Put beam transport channels in each sector to control betatron tunes

Curing the limits of overlapping orbits and controlling tunes opens the high-current frontier:

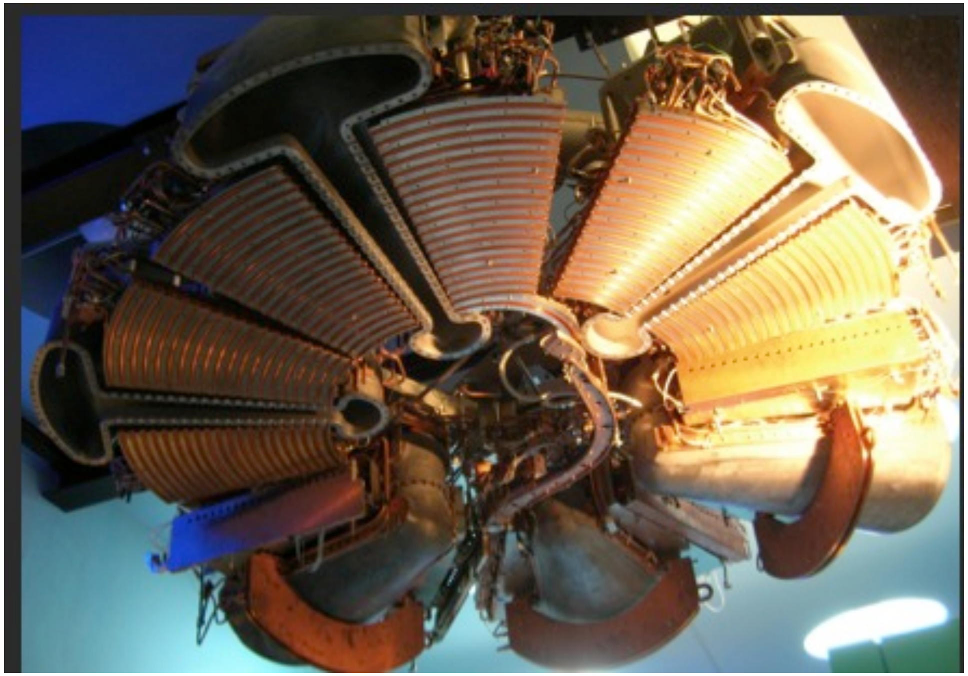
- Proton driver for ADS fission
- Medical Isotope Production
- Ion beam therapy
- Muon Cooling

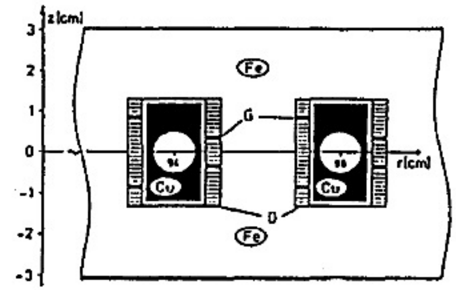
SFC Components



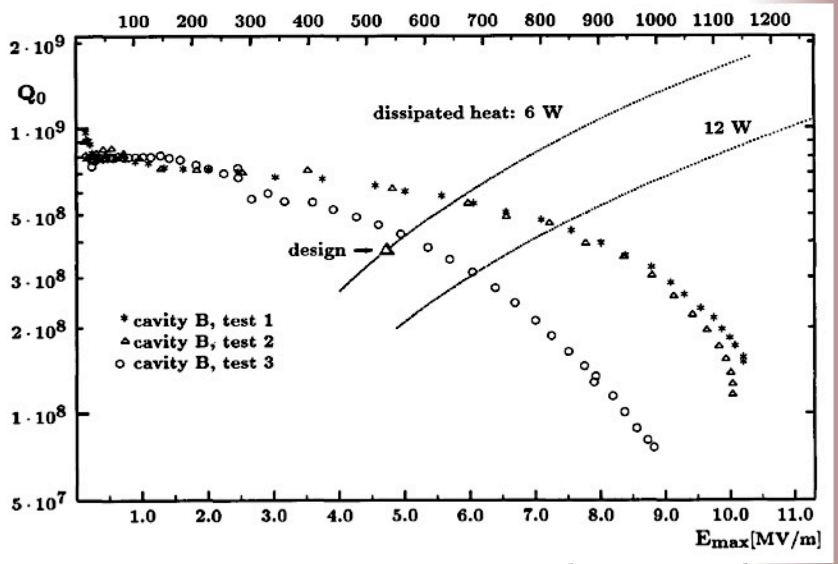
Sectors are simple radial wedges – optimum for integrating SRF

TRITRON was the first to attempt to make a separated orbit cyclotron





The good-field fraction of radial aperture was <50% for each orbit, so admittance was limited.



Energy gain in its superconducting Pb cavities was limited by multipacting.

The intervening years of superferric magnet technology (and now MgB_2) and Nb cavity technology make this a fertile time to make a strong-focusing cyclotron for high current.

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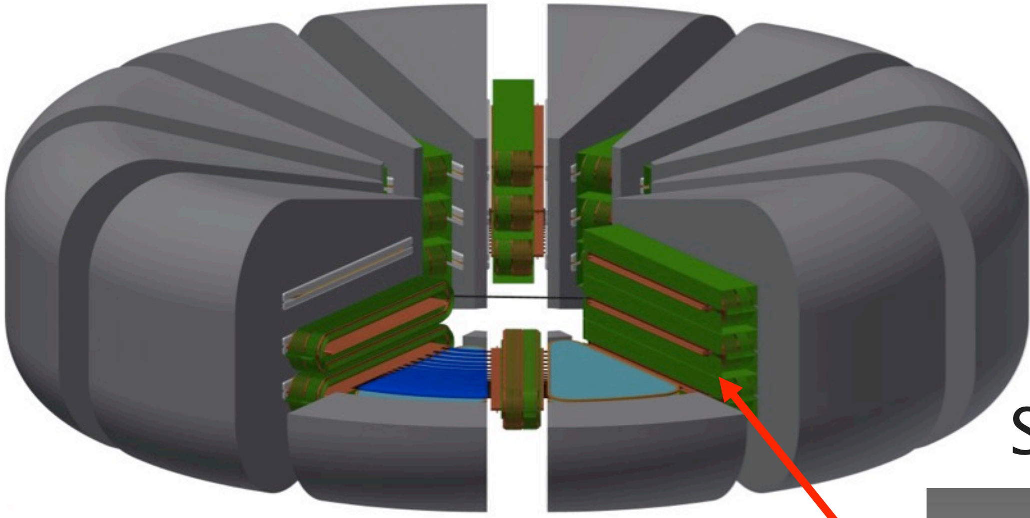
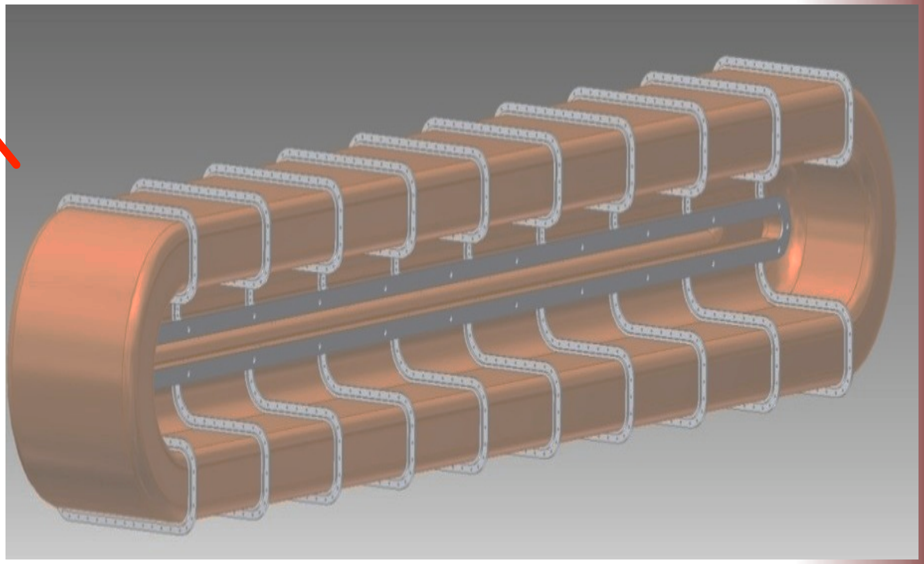
Slot-geometry ¼-wave SRF Cavities

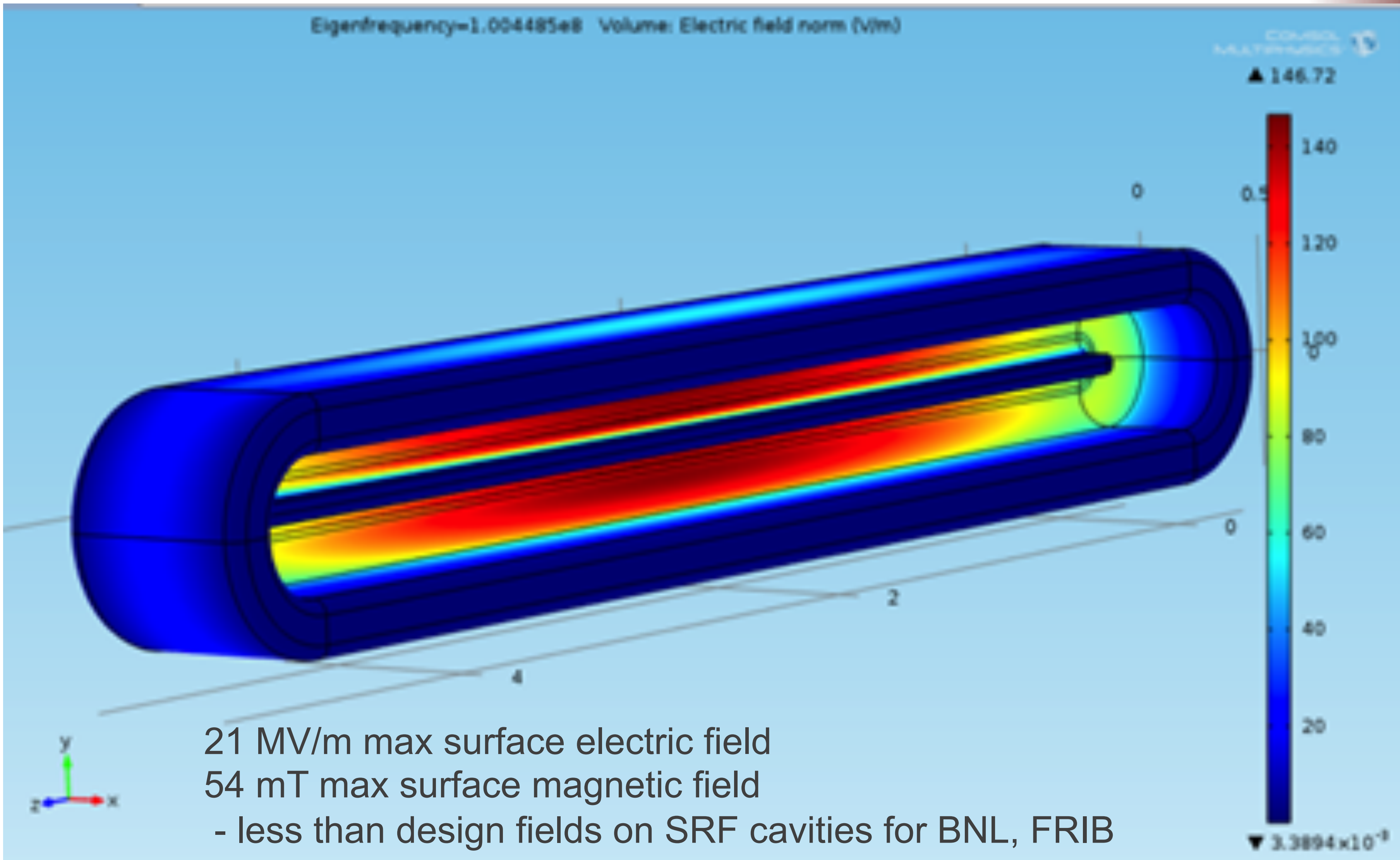


Superconducting RF cavities



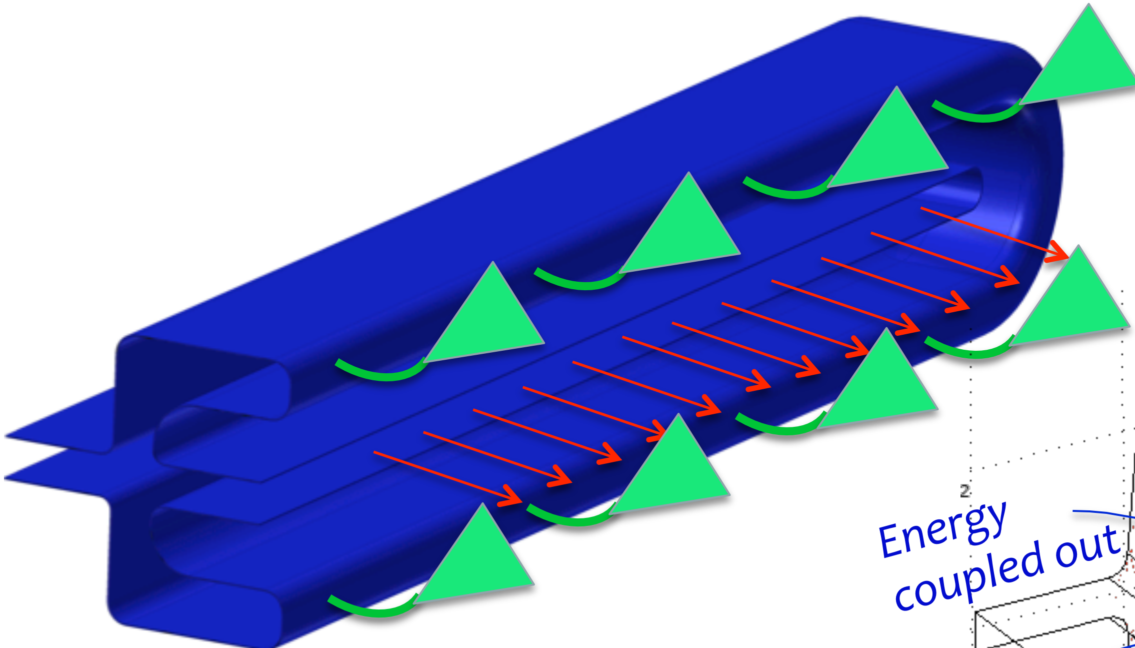
- 100 MHz
- 2 MV/cavity energy gain
- 20 MV/turn fully separates orbits

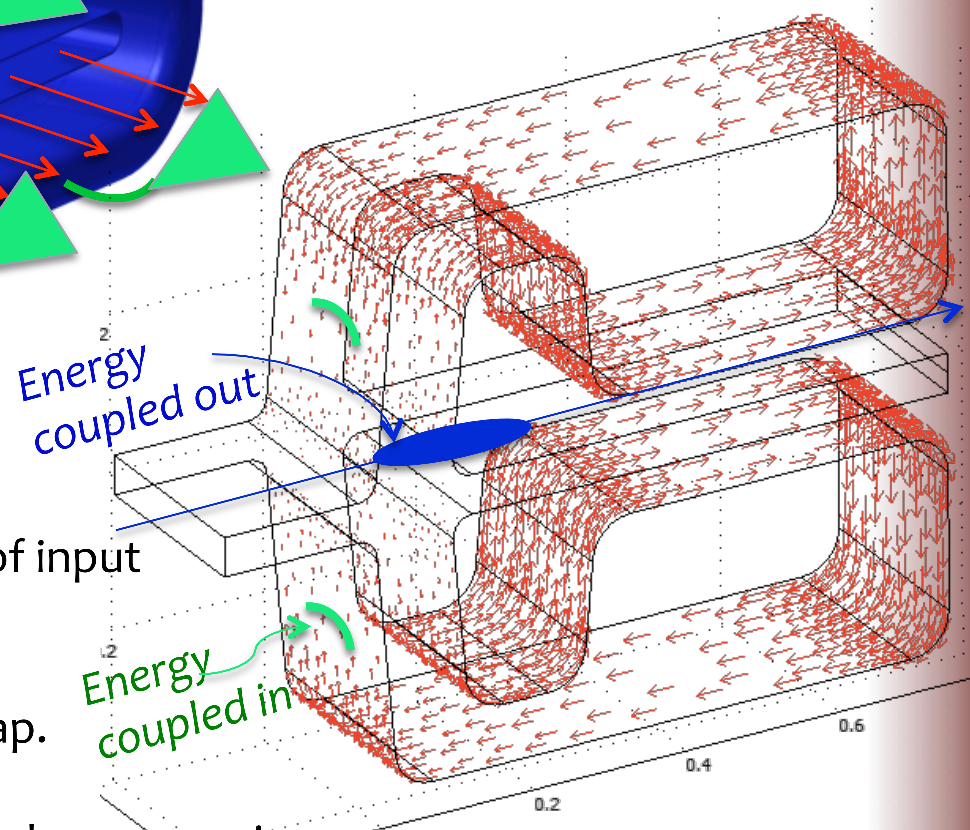
Example SRF Cavity Model



21 MV/m max surface electric field
54 mT max surface magnetic field
 - less than design fields on SRF cavities for BNL, FRIB

Slot-geometry ¼ wave cavity structure and distributed RF drive suppresses perturbations from wake fields





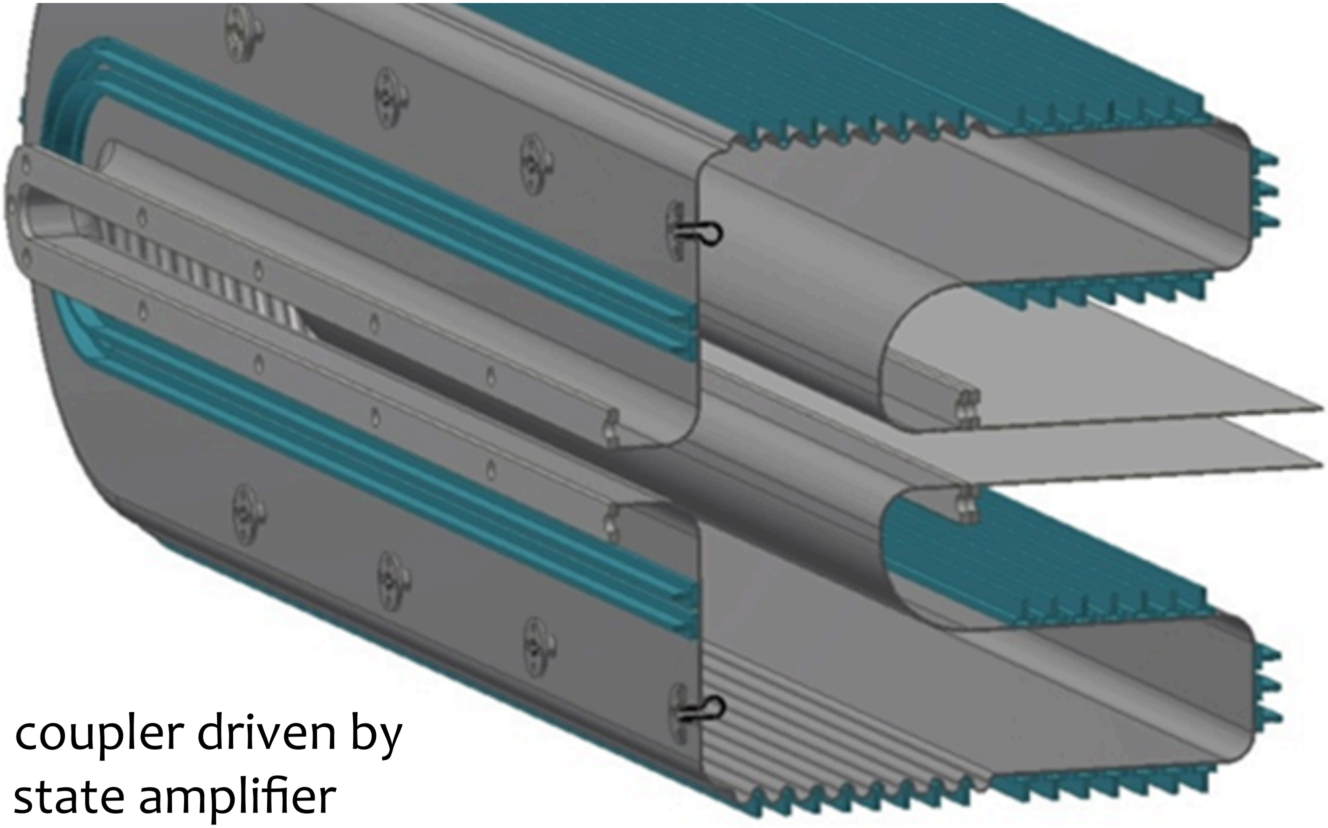
RF power is coupled to the cavity by rows of input couplers along the top/bottom lobes.

RF power is coupled from the cavity to the synchronous bunches traversing the slot gap.

The cavity serves as a linear transformer.

Its geometry accommodates transverse mode suppression

Linear coupler array to match drive to beam loading, convolutes to suppress multipacting



Each coupler driven by solid state amplifier

Distributed drive matches to distributed beam loading for stability under high beam loading.

Note: this requires that all orbits are made very close to isochronicity…

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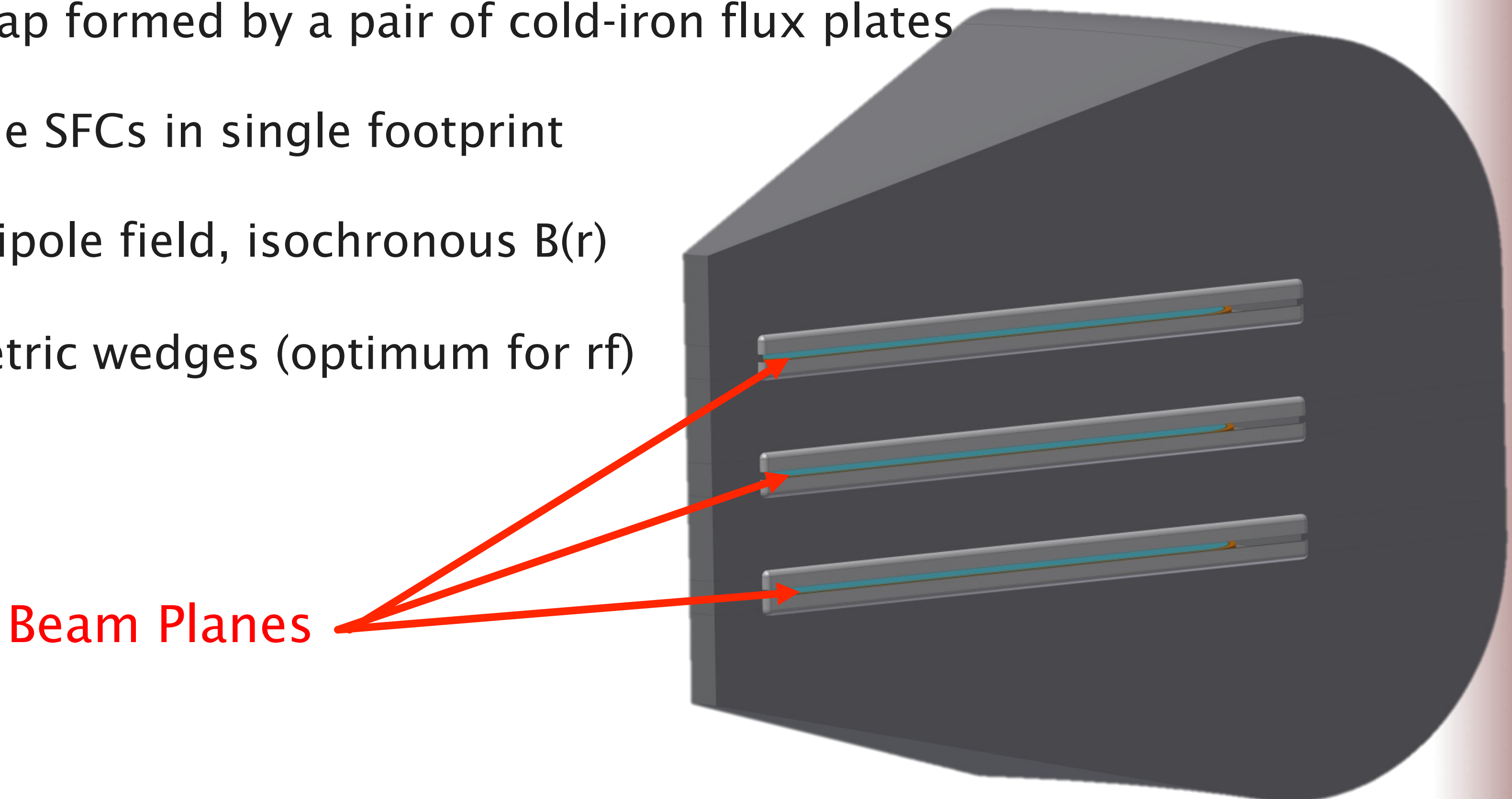
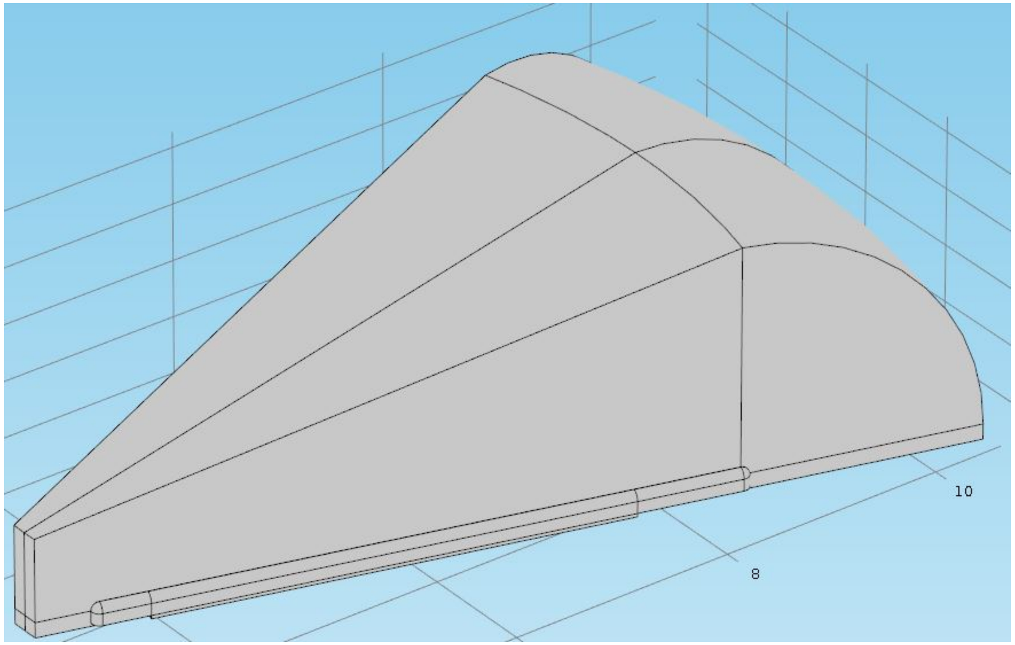
Sector dipoles - Flux-Coupled Stack

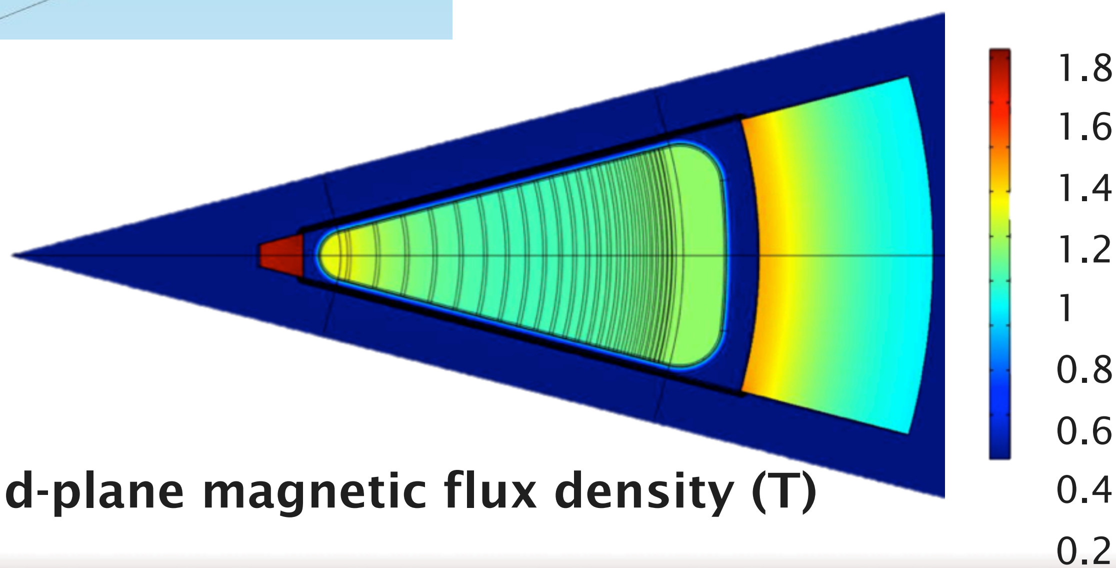
- Levitated-pole design originated at Riken
- Common warm-iron flux return
- Each gap formed by a pair of cold-iron flux plates
- Multiple SFCs in single footprint
- ~1 T dipole field, isochronous B(r)
- Geometric wedges (optimum for rf)



Sector Dipole Modeling



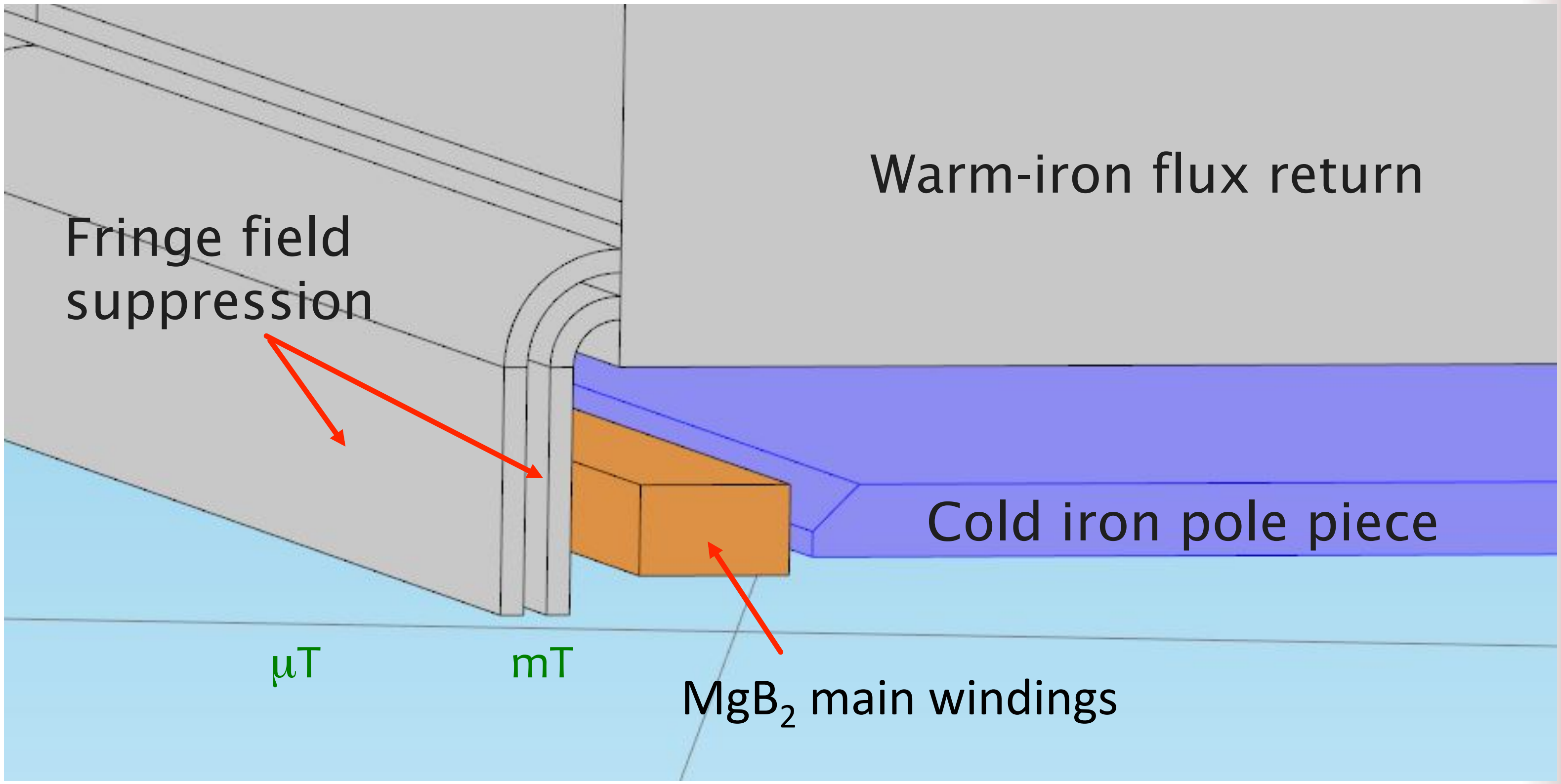
Top half of single stack cyclotron for modeling



Mid-plane magnetic flux density (T)

Fringe Field Reduction

Superconducting cavities require the magnetic flux density to be less than 40 mT 10 cm from the warm iron flux return.



Levitated pole method first pioneered at Riken

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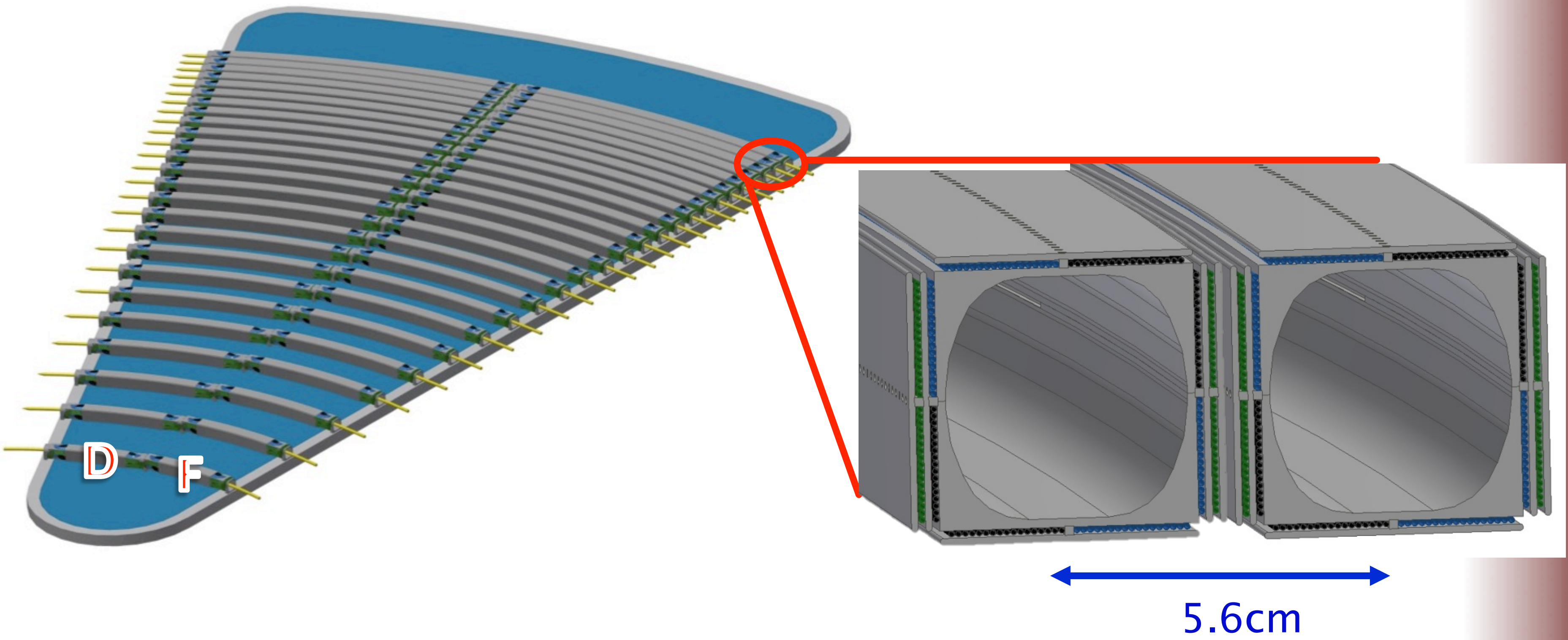
F-D doublet on each orbit, each sector

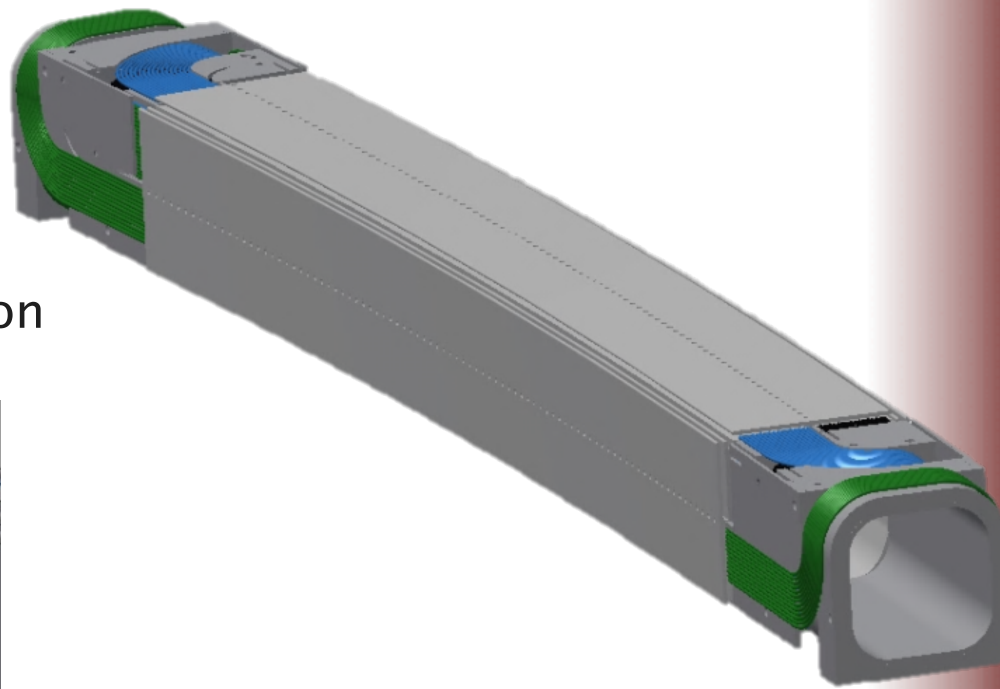


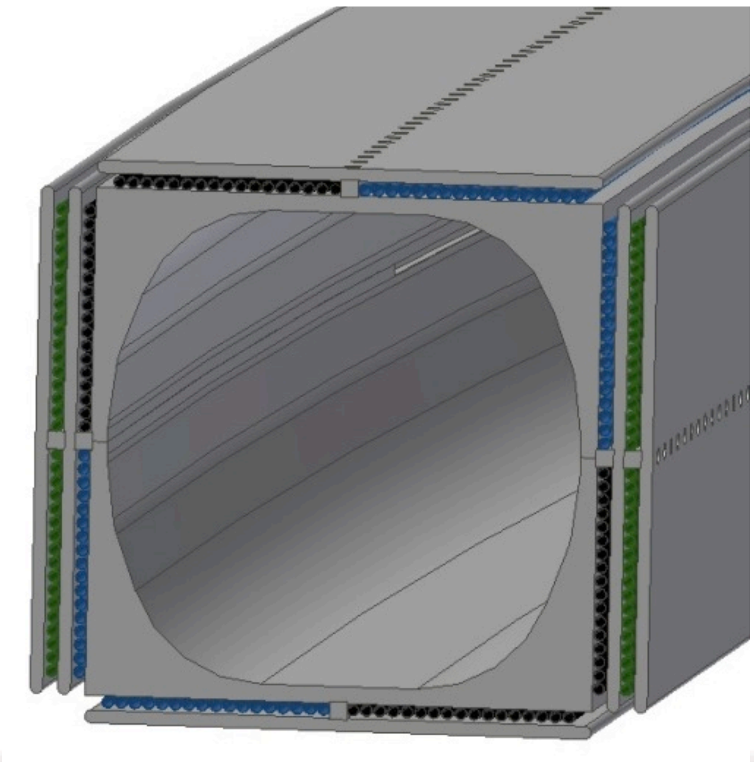
BTC dimension set by beam separation at extraction

>80% of horizontal aperture is useful for orbits.

Beam Transport Channel (BTC)

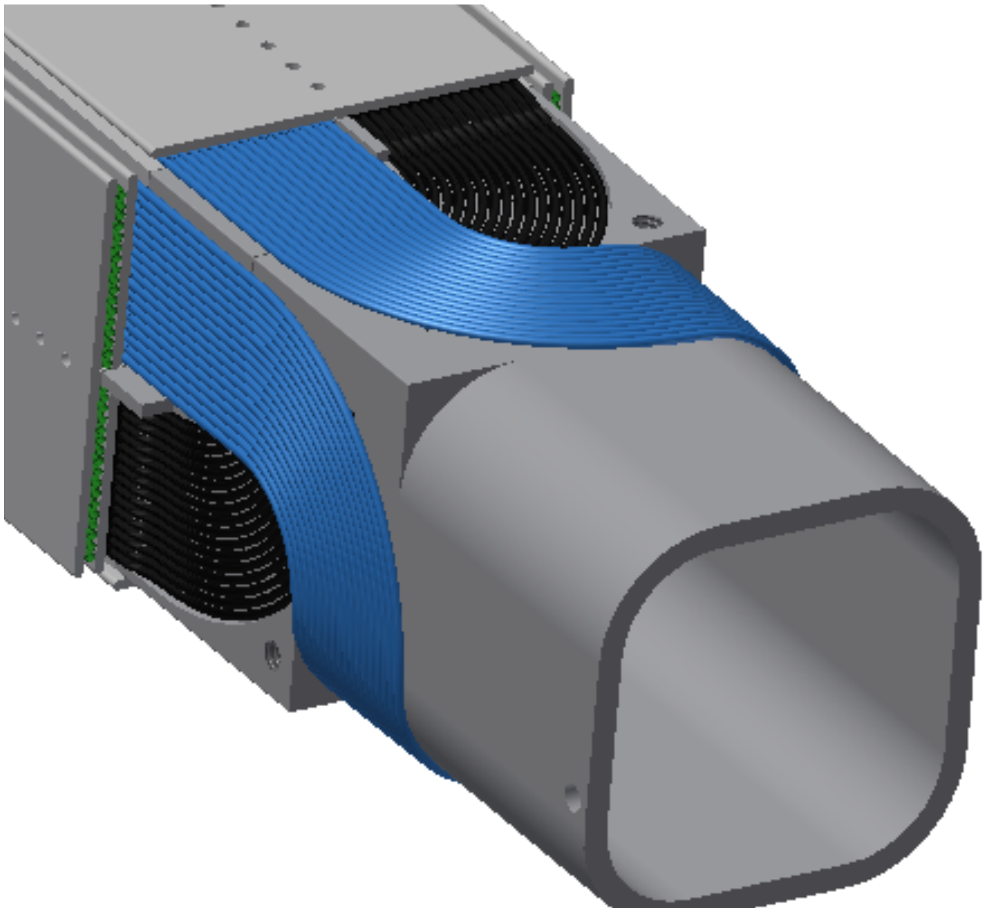
Dipole Windings
- Up to 20 mT
- Correctors for isochronicity,
- Full-aperture injection/extraction





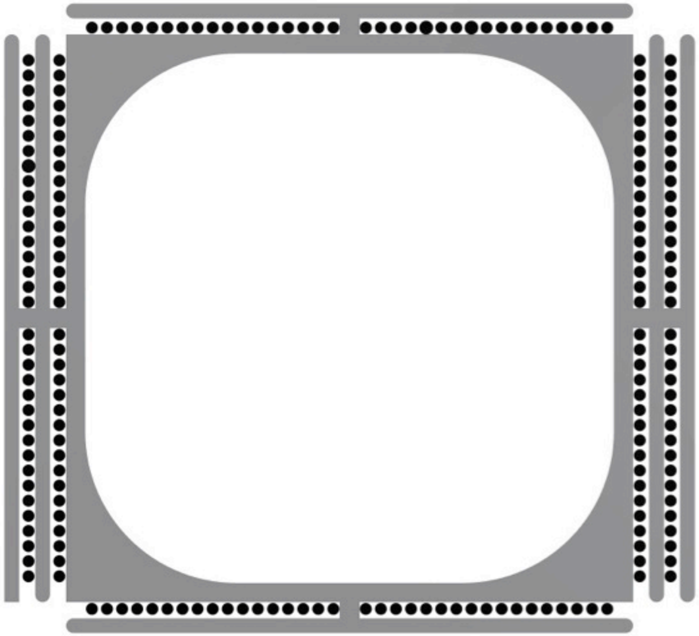
Quadrupole Windings
- Up to 6 T/m
- Panofsky style
- Alternating-gradient focusing
- Powered in 6 families to provide total tune control

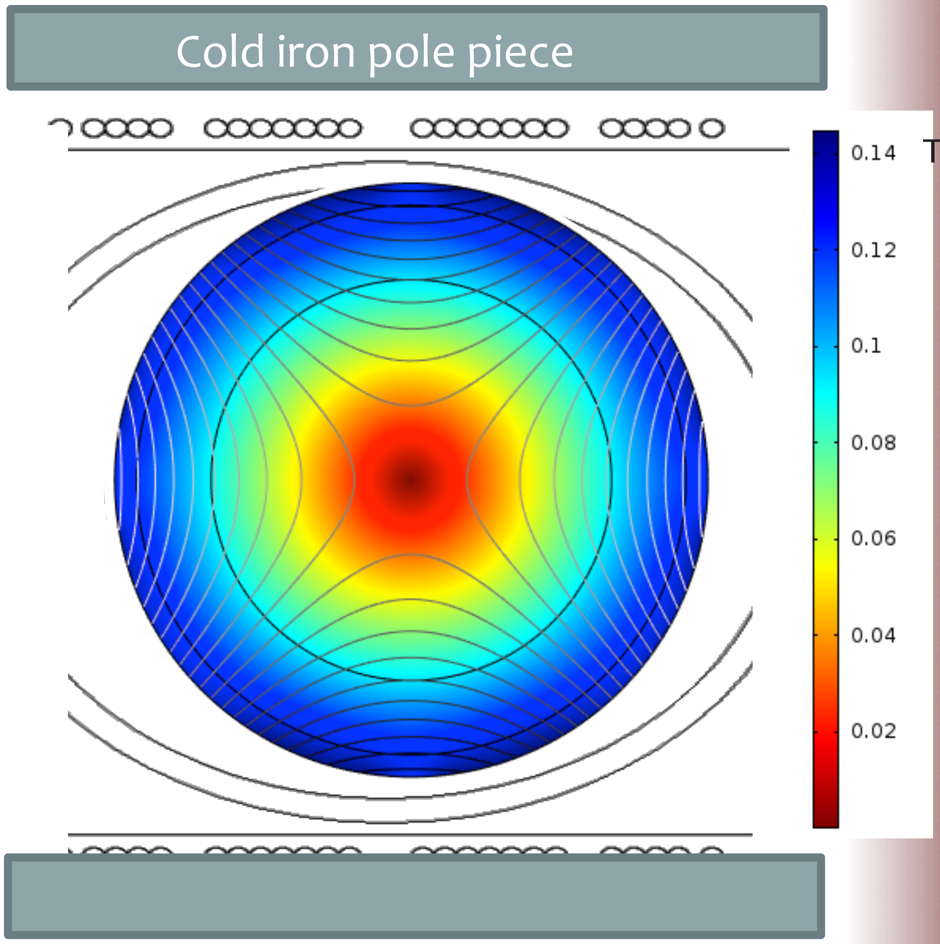
All BTC windings use MgB_2



Operate with 15-20 K refrigeration cycle
10 x less AC power to refrigerate,
50 x more heat capacity compared to NbTi @ 4.2 K

2D Field Modeling

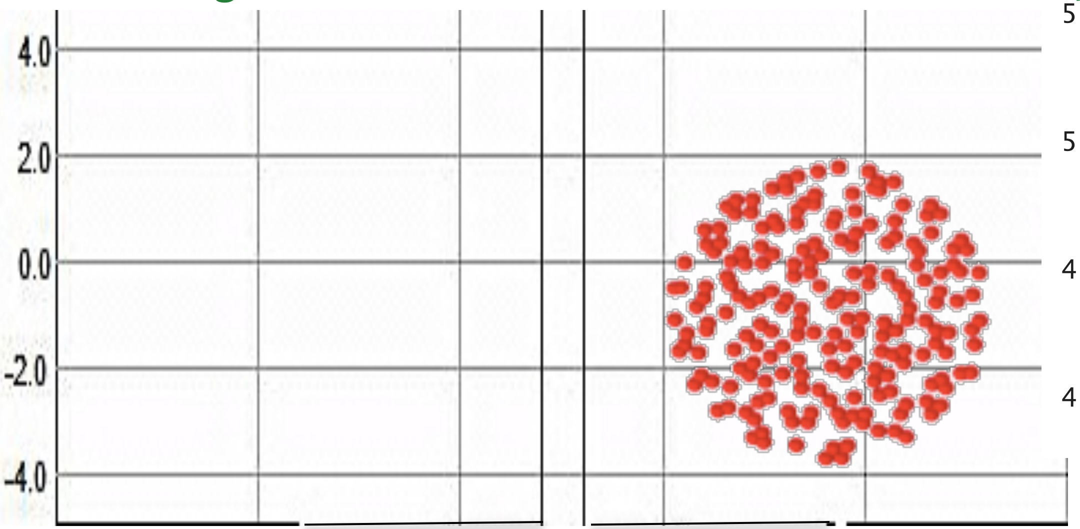


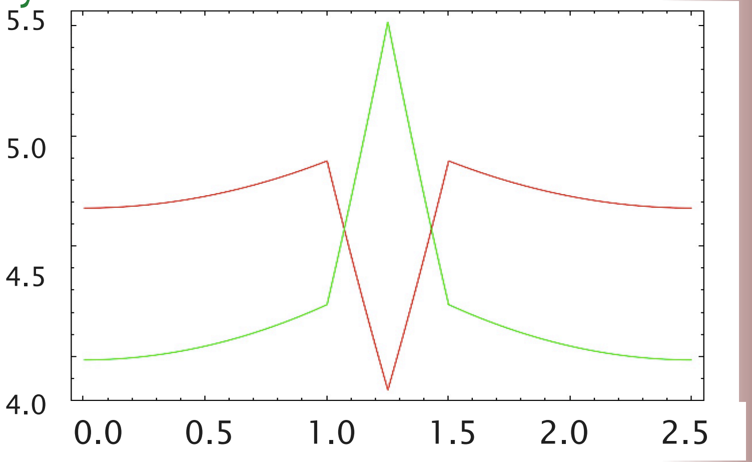


Wire spacing adjusted to kill multipoles
Current density required for 6T/m ~ 235 A

F-D quads control betatron motion

Uniform gradient in each channel: excellent linear dynamics.



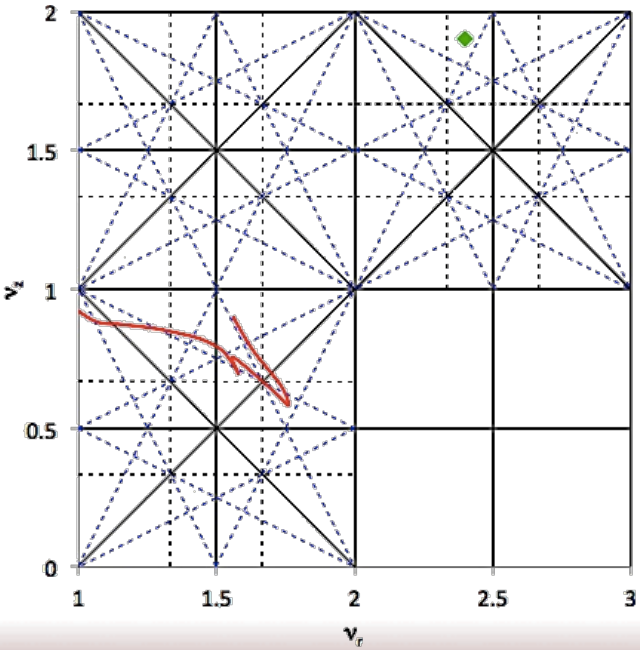


We can lock ν_x, ν_y to any desired operating point.

BTC quads are tuned in 2 x 5 families.

Sextupole correctors at exit of each BTC are tuned in 2 x 6 families.

First 2 turns each have dedicated families so that they can be tuned first for rational commissioning.



We have developed a simulation platform that takes high-current bunches through the spiral orbit, treating it as a spiral transfer line.

Overview of Received Contributions

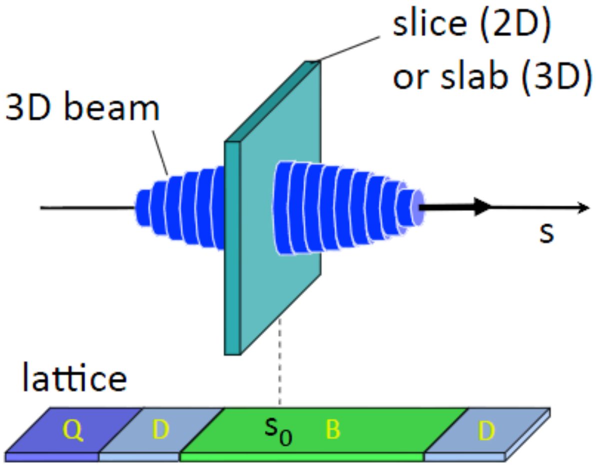
- Synergia
- Orbit-ORNL ← Later
- ORBIT-BNL
- Simpsons ← No access
- PTC/MADX & ORBIT-ORNL
- Accsim — No access
- ML/IMPACT - MaryLie Impact
- Warp
- OPAL - Object Oriented Parallel Accelerator Library ← Later

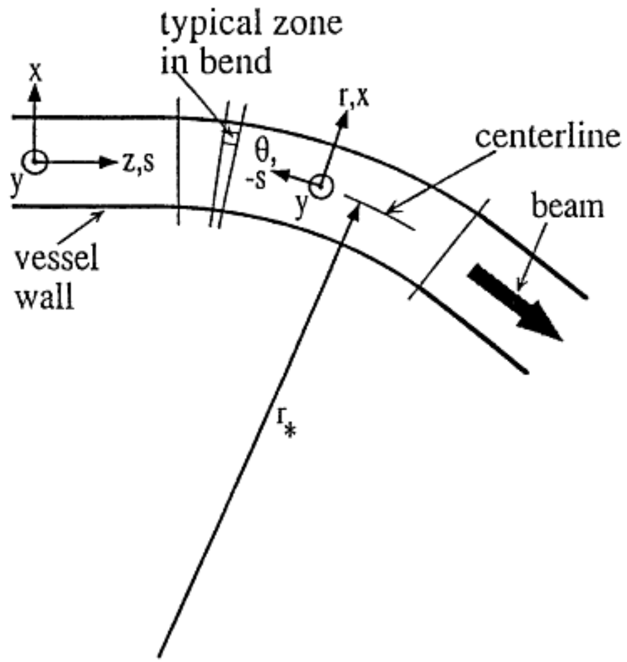
- Elegant
- Hyper_TAMU, MPI_TAMU

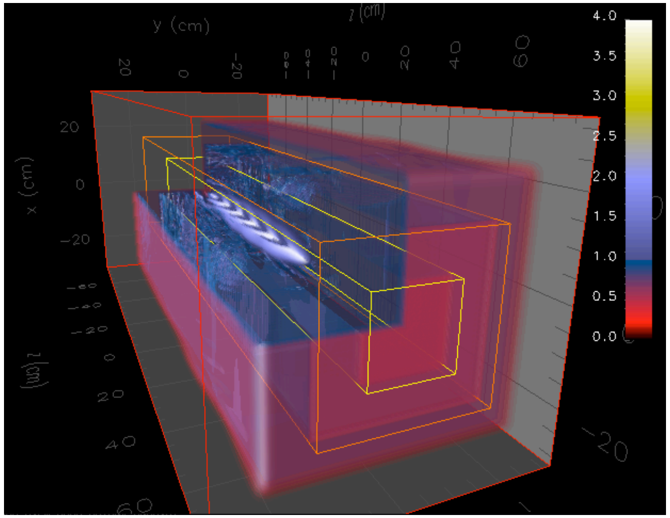
Accounts for details of 6-D dynamics:

- resonance dynamics,
- synchro-betatron couplings,
- space charge,
- wake fields
- beam loading

Coordinates, Mesh, Global coordinates, Beam assumptions…







Equations of motion are nonlinear, coupled, damped:

$$\frac{d\vec{p}}{dt} = q\cdot\left(\vec{v}\times\vec{B}+\vec{E}\right) = \vec{F}$$

$$+ \quad p_w = \beta_w \gamma \cdot mc$$

$$+ \quad dt = ds/\beta_z c$$

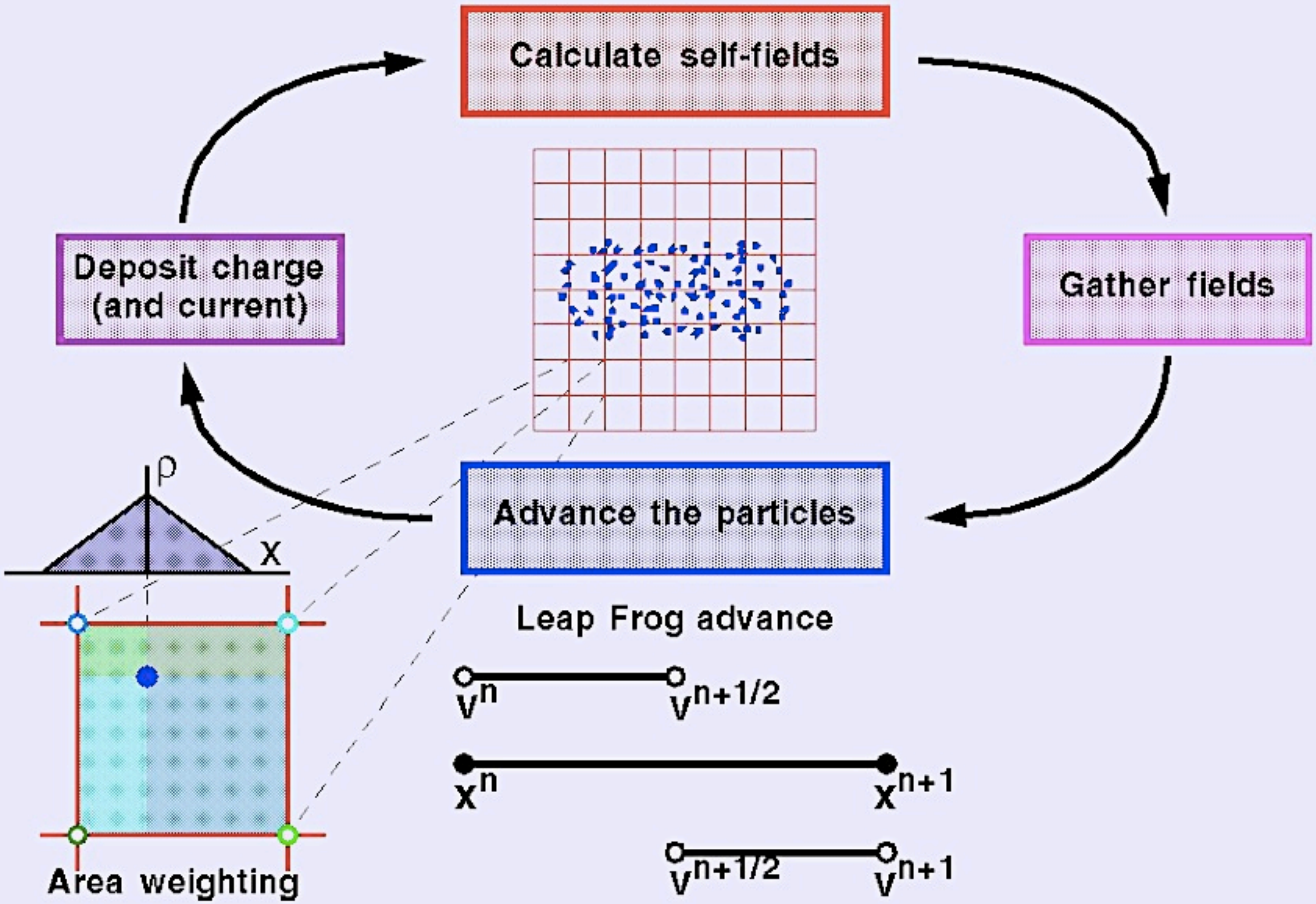
$$\begin{cases} \dfrac{d\gamma\beta_x}{ds} = \dfrac{F_x}{mc^2\beta_z} = \dfrac{d\gamma\beta_z x'}{ds} \\ \dfrac{d\gamma\beta_y}{ds} = \dfrac{F_y}{mc^2\beta_z} = \dfrac{d\gamma\beta_z y'}{ds} \\ \dfrac{d\gamma\beta_z}{ds} = \dfrac{F_z}{mc^2\beta_z} \end{cases}$$

$\beta_w c$ is the particle velocity along w direction
γ is the particle reduced energy,
q and m its charge and rest mass.
x and y are transverse directions,
s is the abscissa along longitudinal direction z,
x' and y' are called the particle slopes.

$$x'' + \frac{d\gamma\beta_z/ds}{\gamma\beta_z}x' = \frac{F_x}{mc^2\gamma\beta_z^2}$$

The code enables us to make a **self-consistent solution** for B(r); RF ΔE(r) and ϕ(r), BTC gradients, BTC trim dipoles, sextupoles to simultaneously provide **isochronicity, constant tunes, stable phase advances.**
It then tracks, generates Poincare plots, etc for desired bunch properties.

PIC method



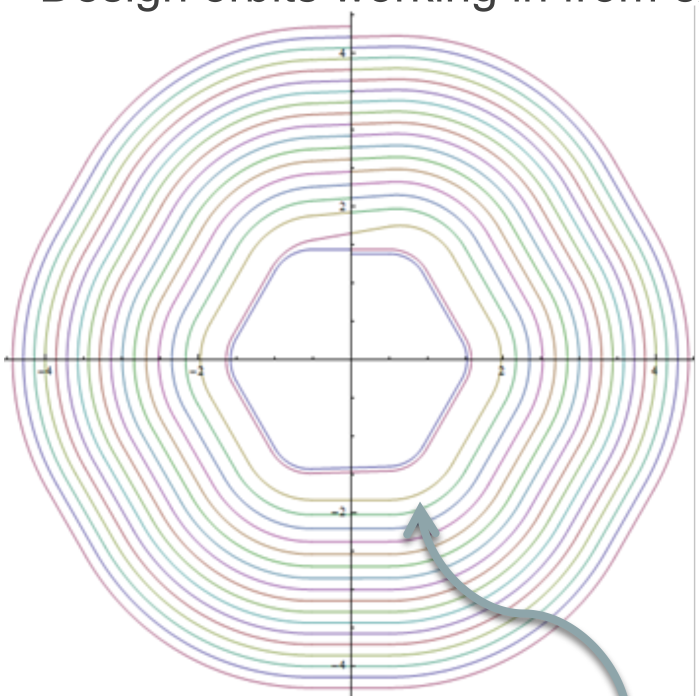
Calculate self-fields
Gather fields
Advance the particles
Deposit charge (and current)
ρ
x
Area weighting
Leap Frog advance
v^n
$v^{n+1/2}$
x^n
x^{n+1}
$v^{n+1/2}$
v^{n+1}

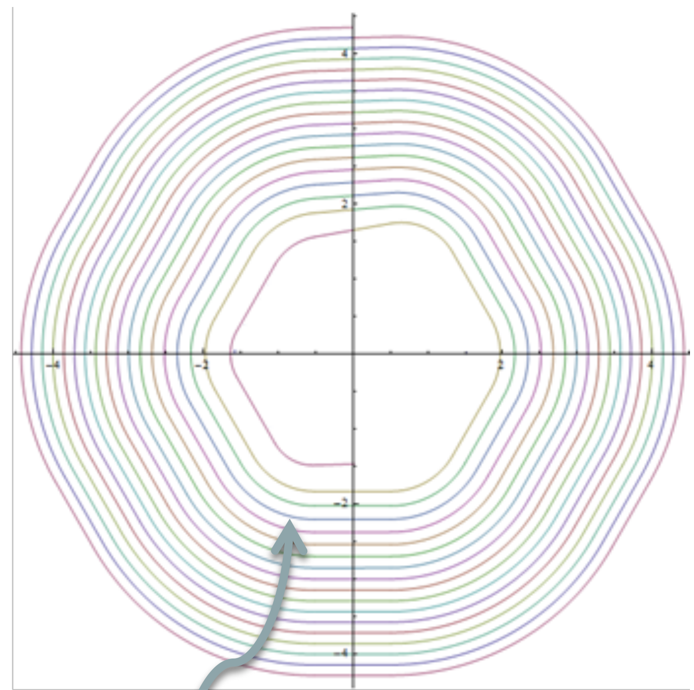
Dipole Corrector

The BTC dipole correctors are used to maintain isochronicity and locally manage beam spacing at injection, extraction.

Example of ability to adjust orbits to optimize design (from a 6 sector 100 MeV SFC design):

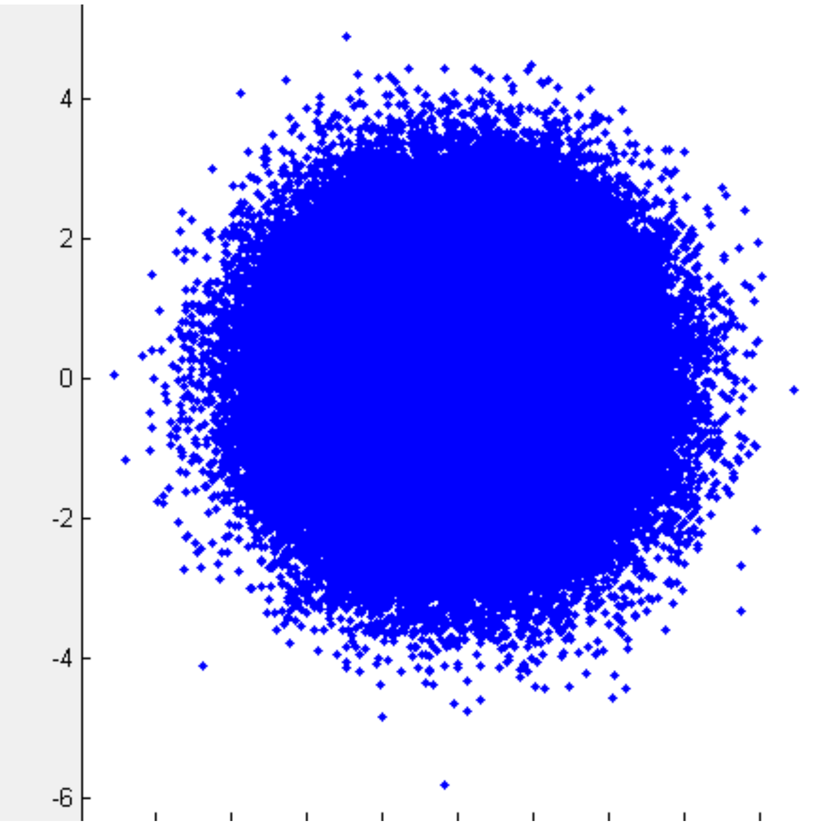
Design orbits working in from extraction:



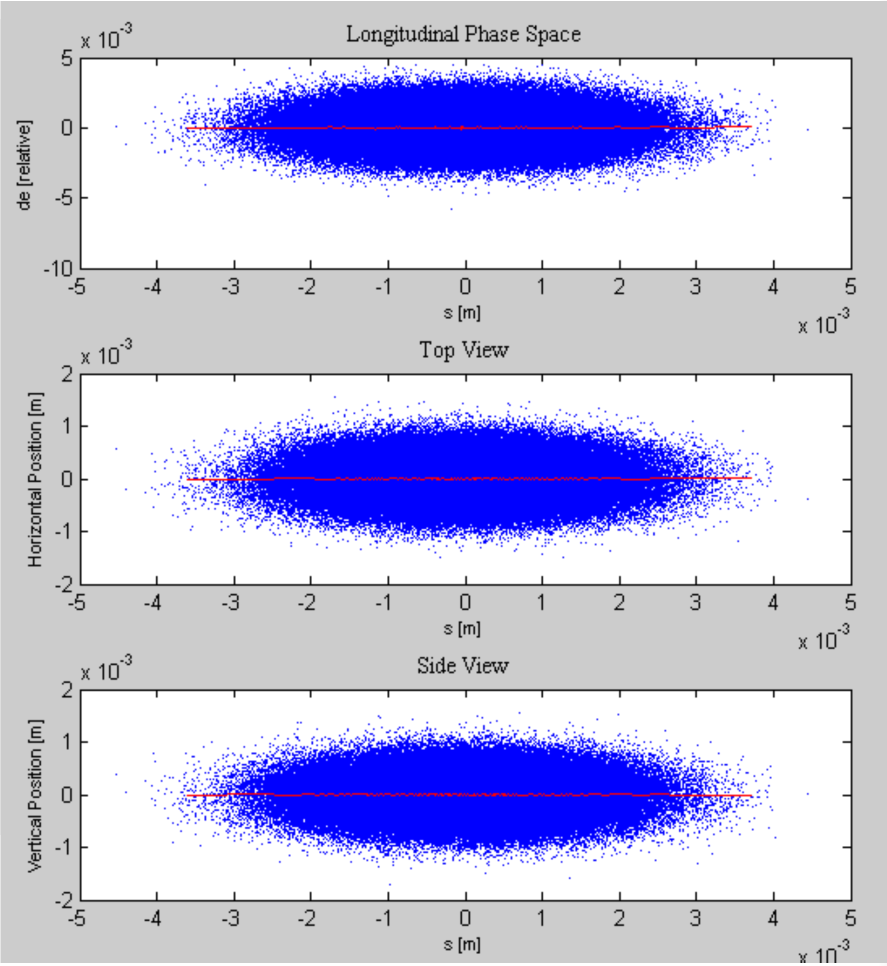


First try gave problematic orbits @ injection
Then adjust orbit pattern using dipole correctors – ideal accommodation for injection

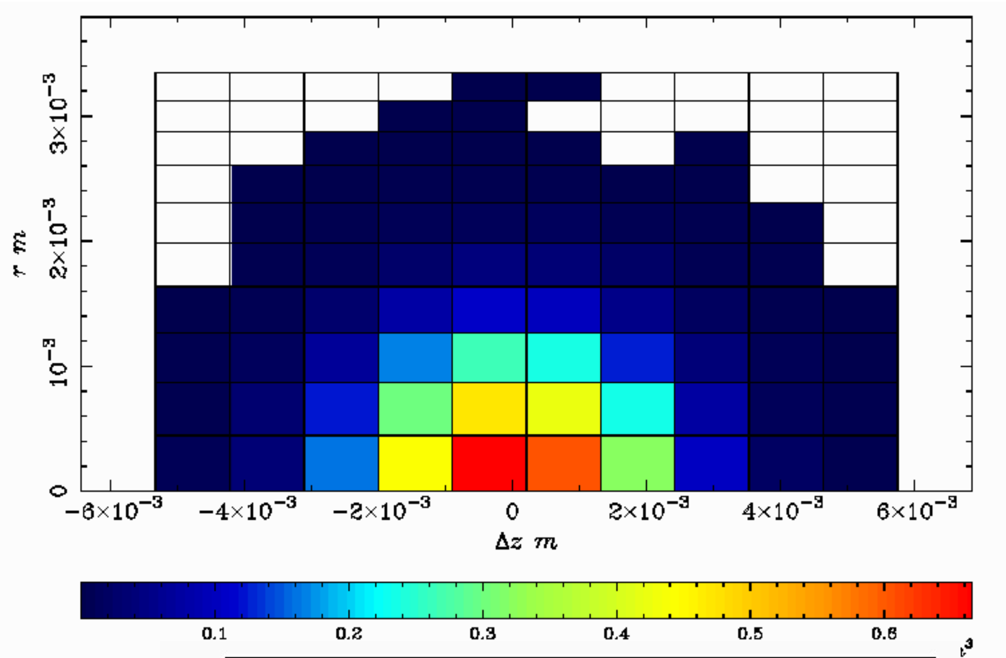
We are now modeling 6-D transport through the SFC including effects of x/y coupling, synchrobetatron, and space charge

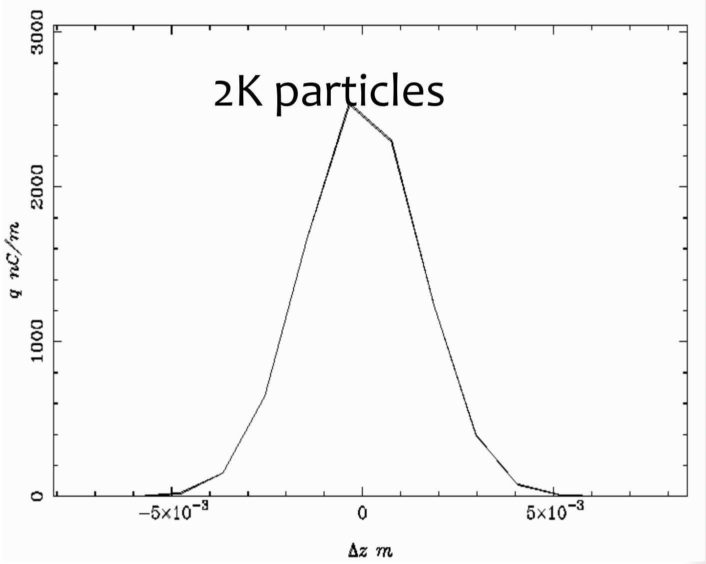


300k particle simulation

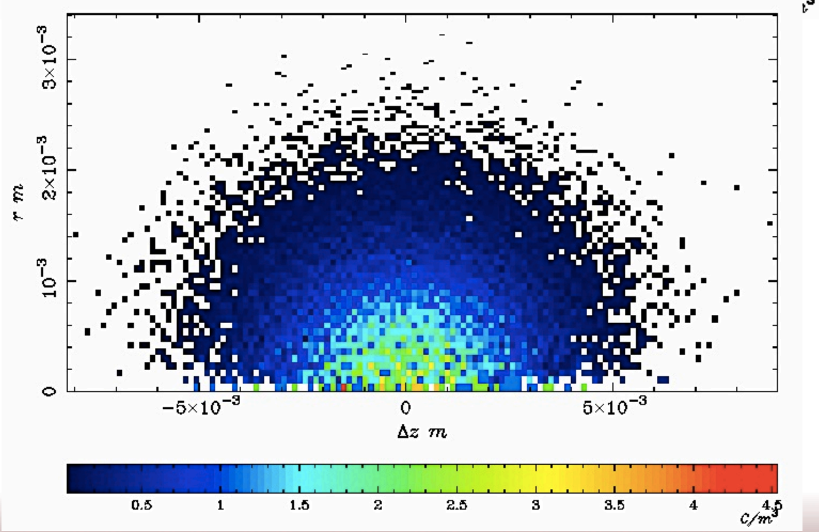


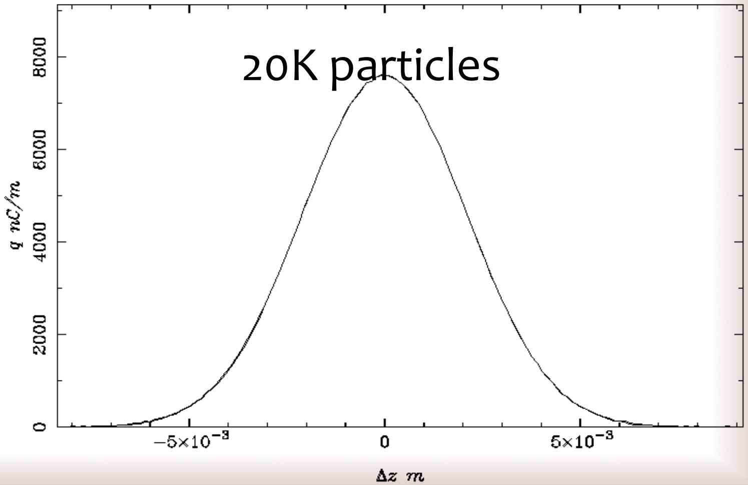
Charge Density for 10 mA beam



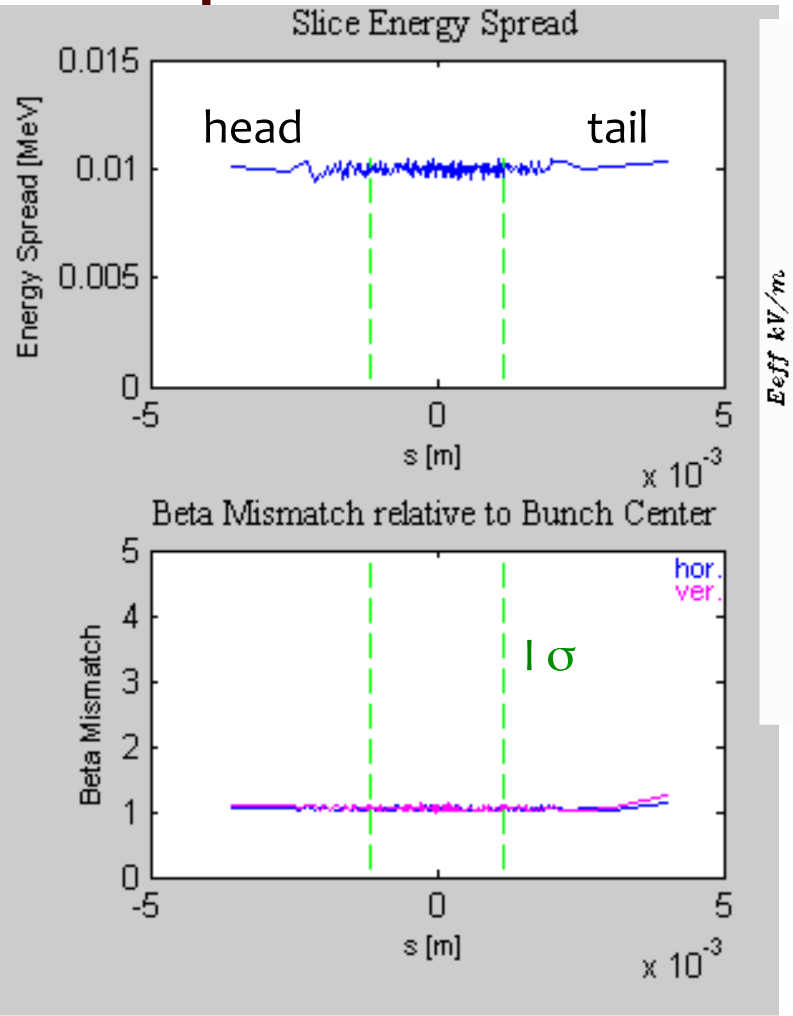


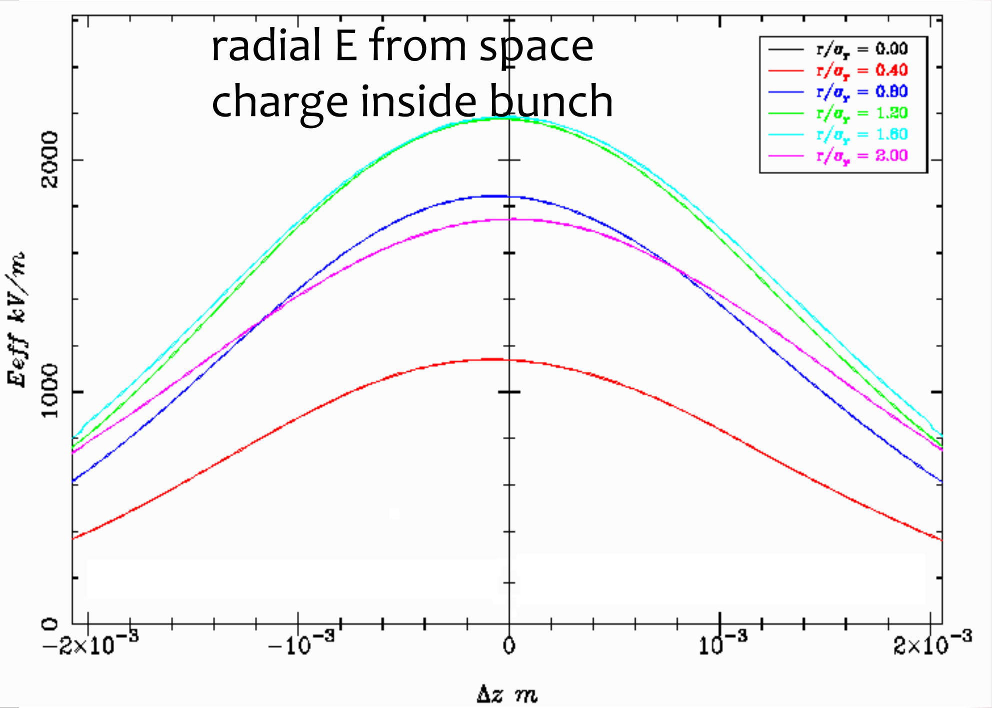
Longitudinal charge distribution





Matched optics from injection to extraction. Left pictures shows how a bunch transfers

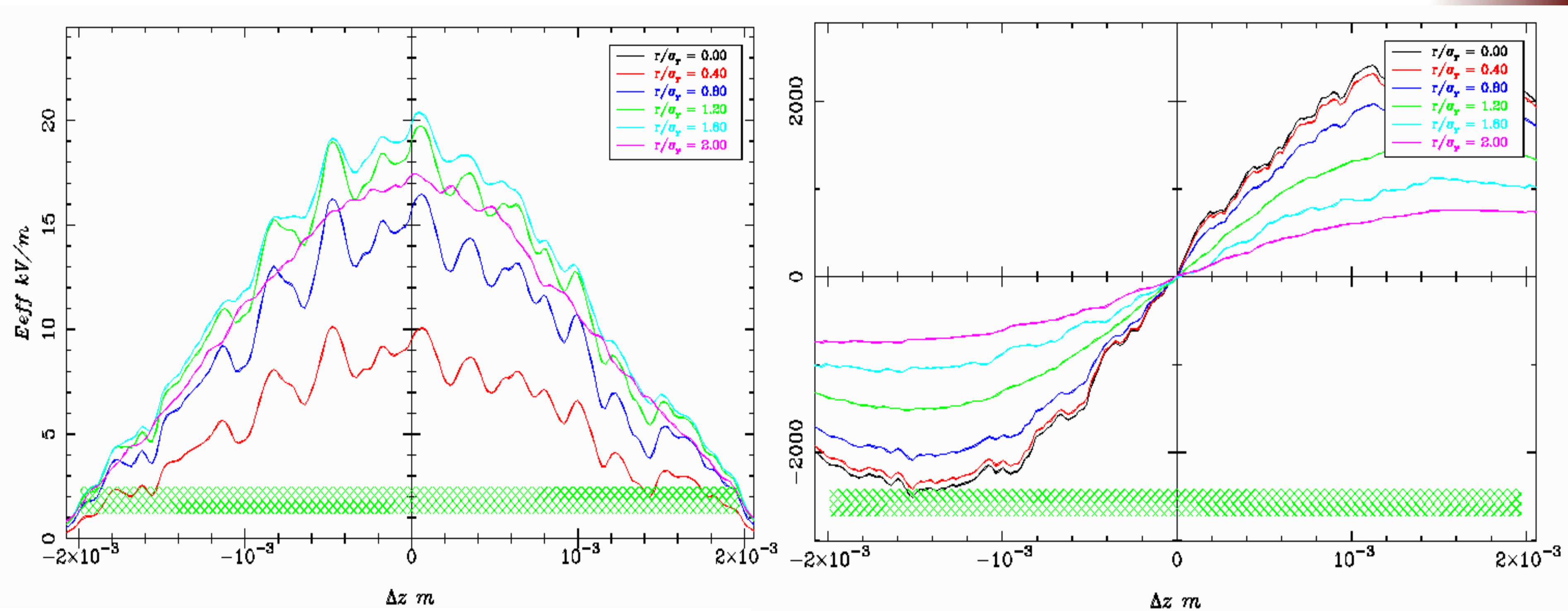




10 mA beam, ± 5° total phase width

Plots of slice energy spread and β mismatch after first turn, sensitive to bunch length – no hourglass from synchrobetatron

Effect of ±.3 MeV energy mismatch on a bunch injected at 9 MeV

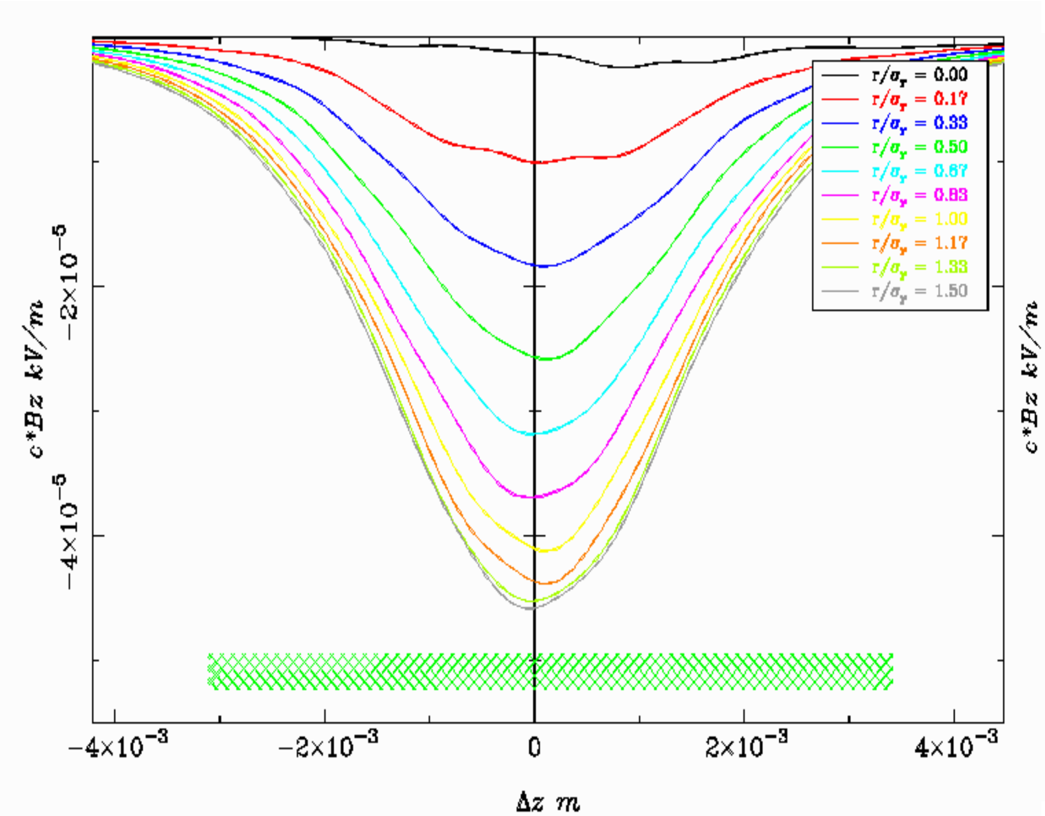


bunch is clumping after half-turn (after 2 cavities)

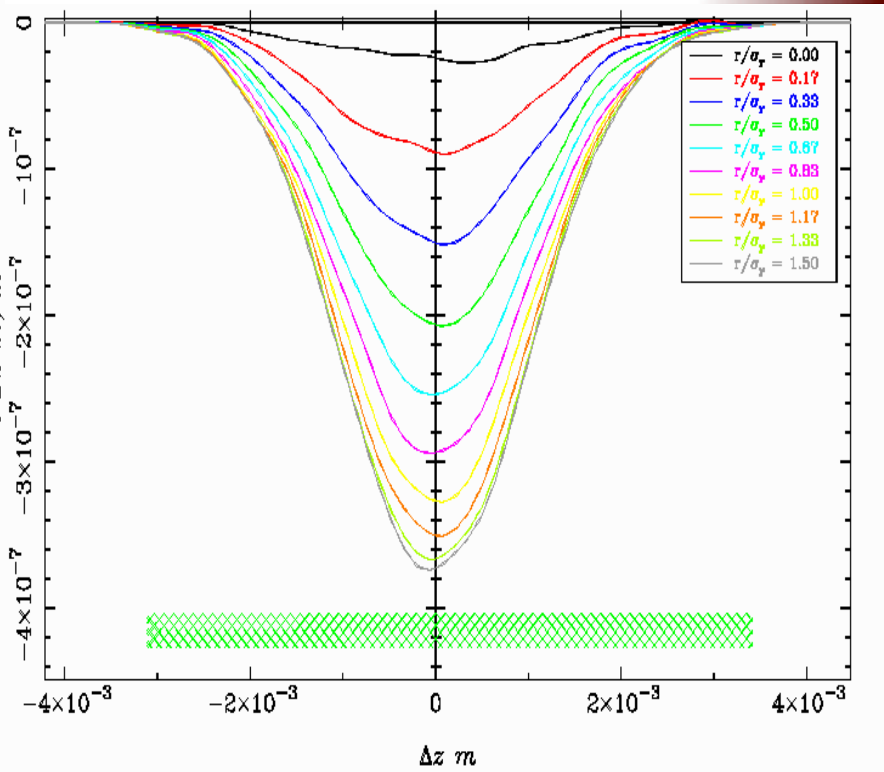
Longitudinal line charges along a bunch - 10 mA beam, injected at 9 MeV.

Radial E from space charge

Distortion in distribution comes from the space charge



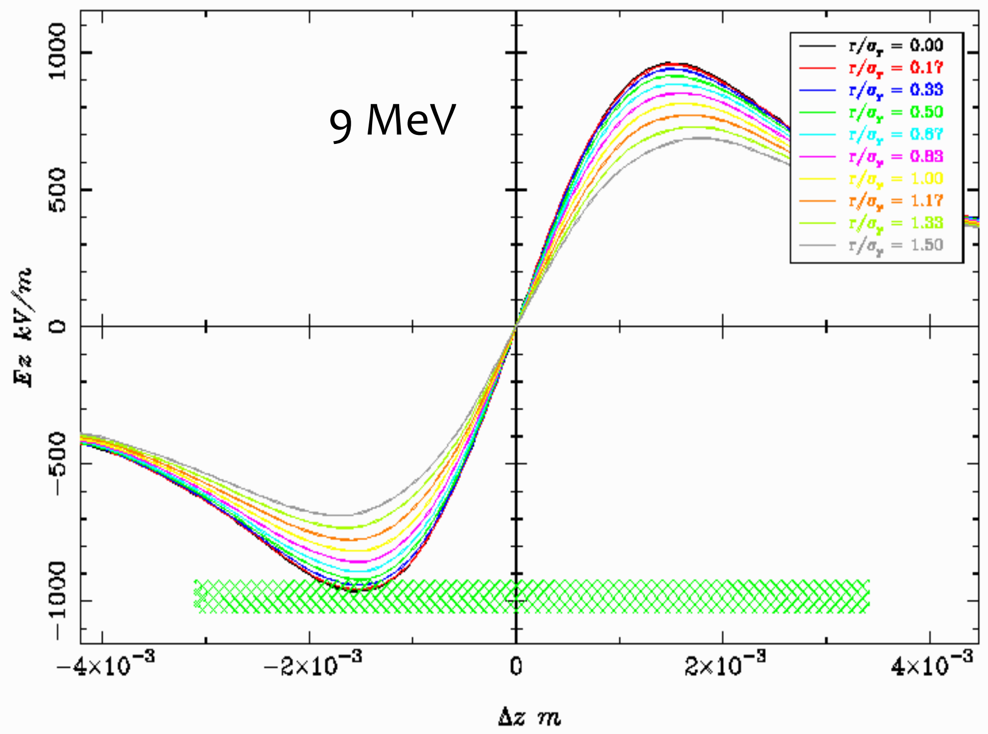
After first cavity

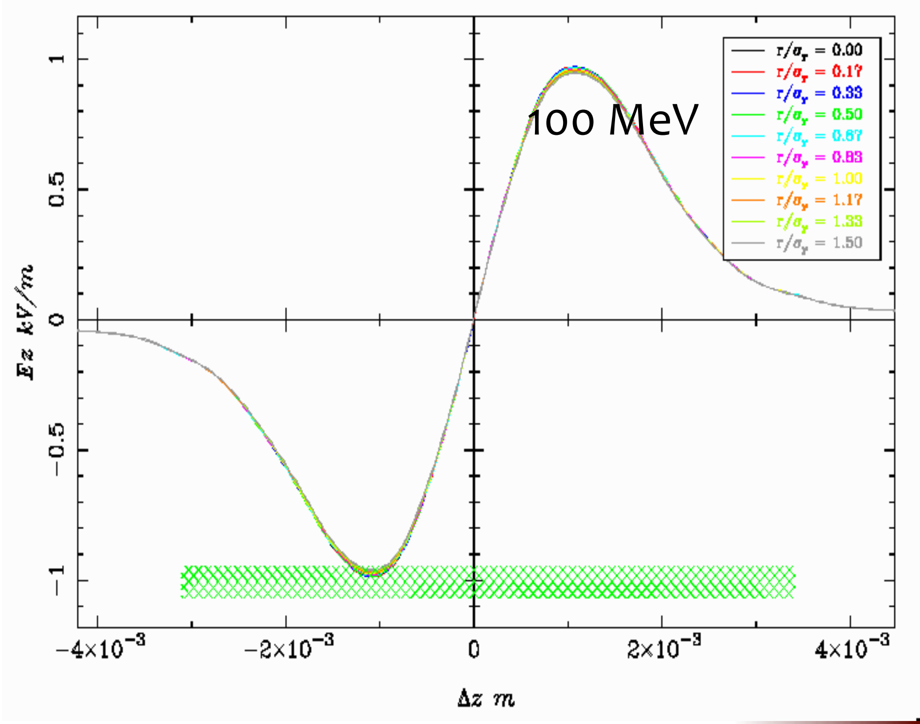


just before extraction

Accelerating bunch at injection, extraction

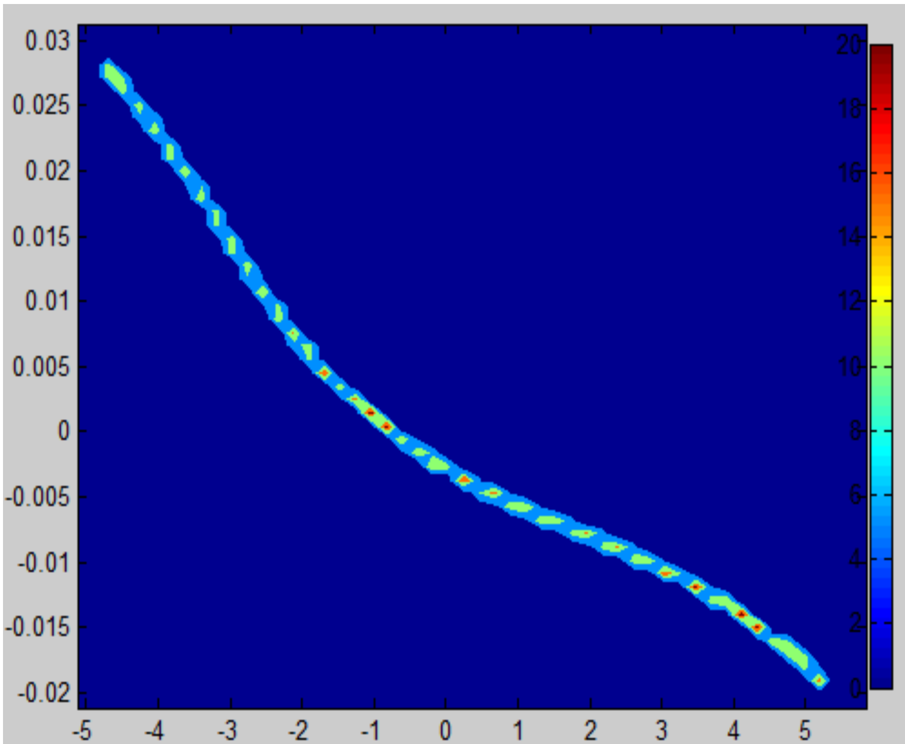
Axial E from space charge





Longitudinal phase space with 10 mA

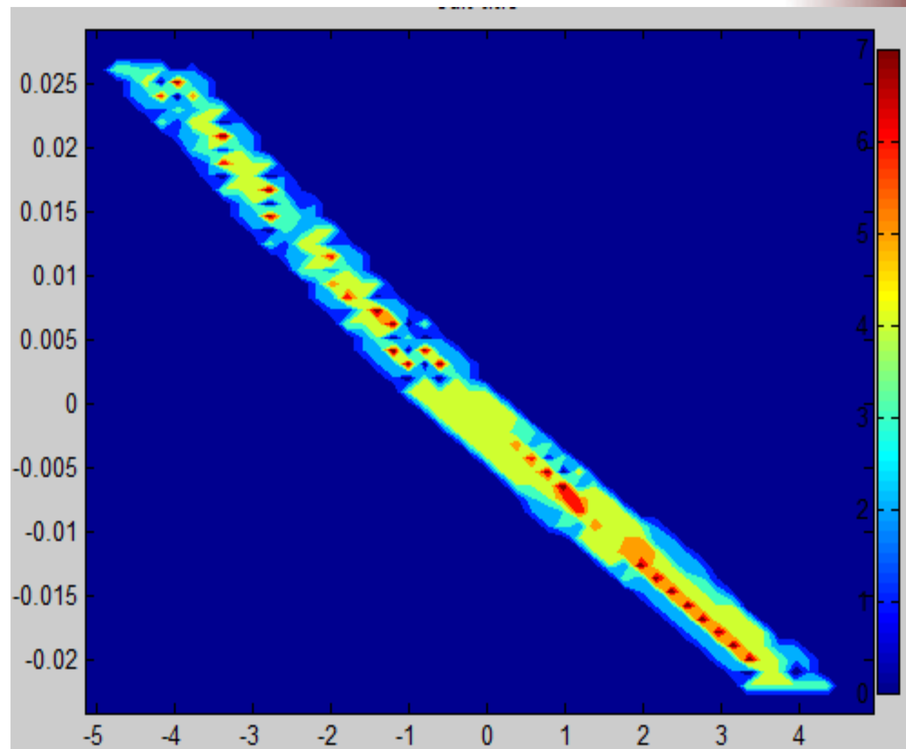
9 MeV injection



±5° phase width

Energy width increases ~30%.

100 MeV extraction



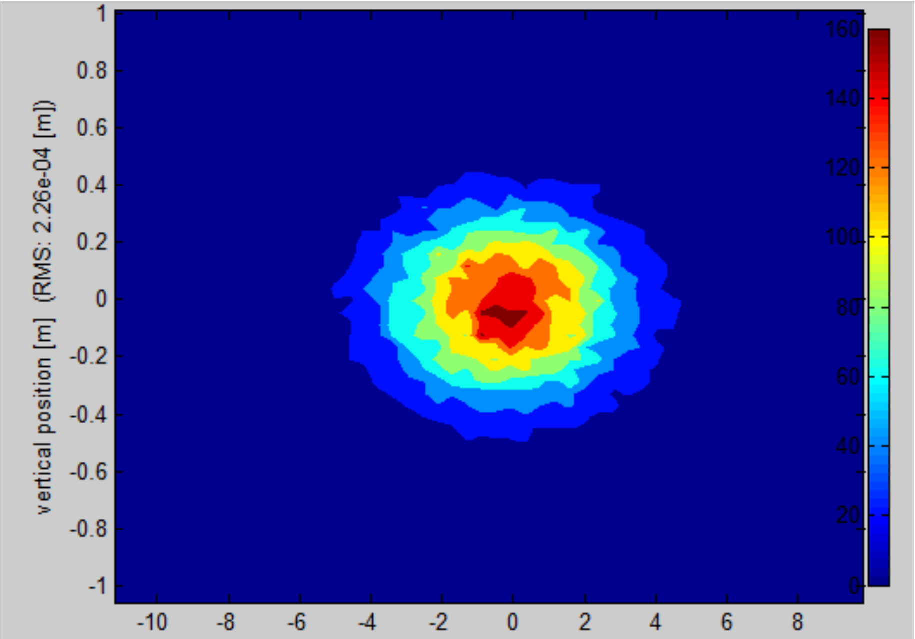
±6° phase width

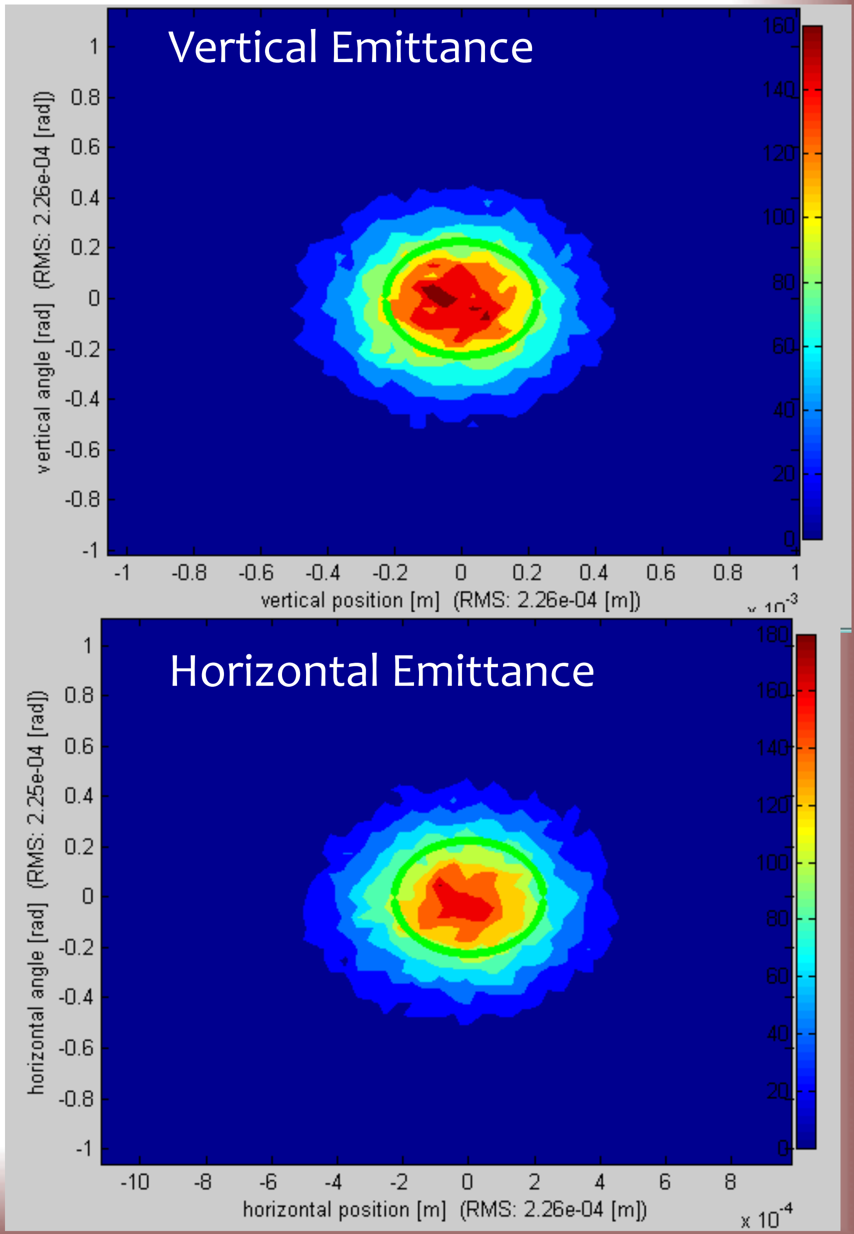
Sextupole correction at exit from each BTC (2 x 6 families)

Transverse phase space of 10 mA bunch through acceleration:

First at injection:

x/y profile

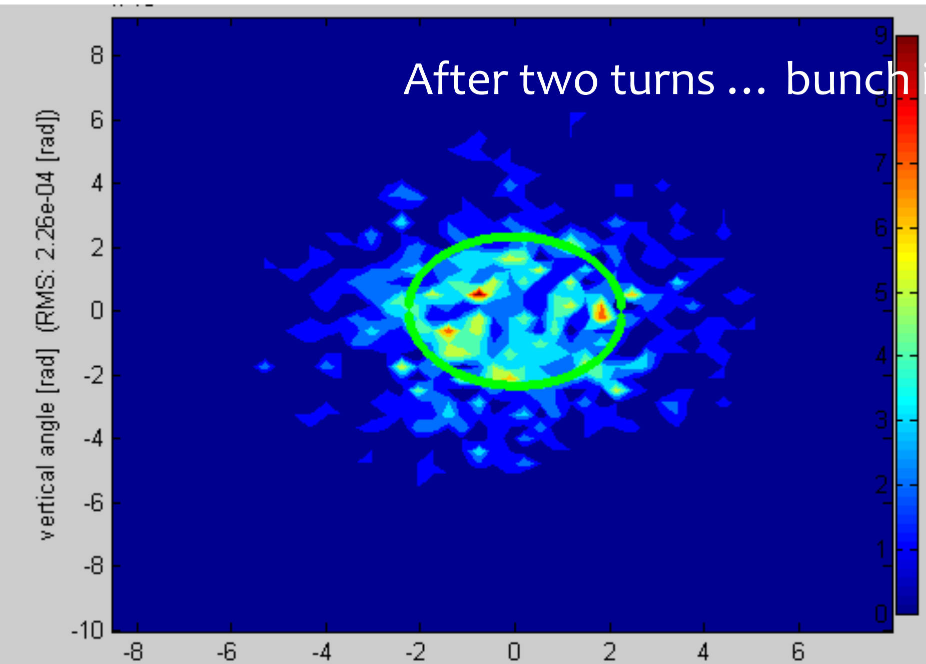




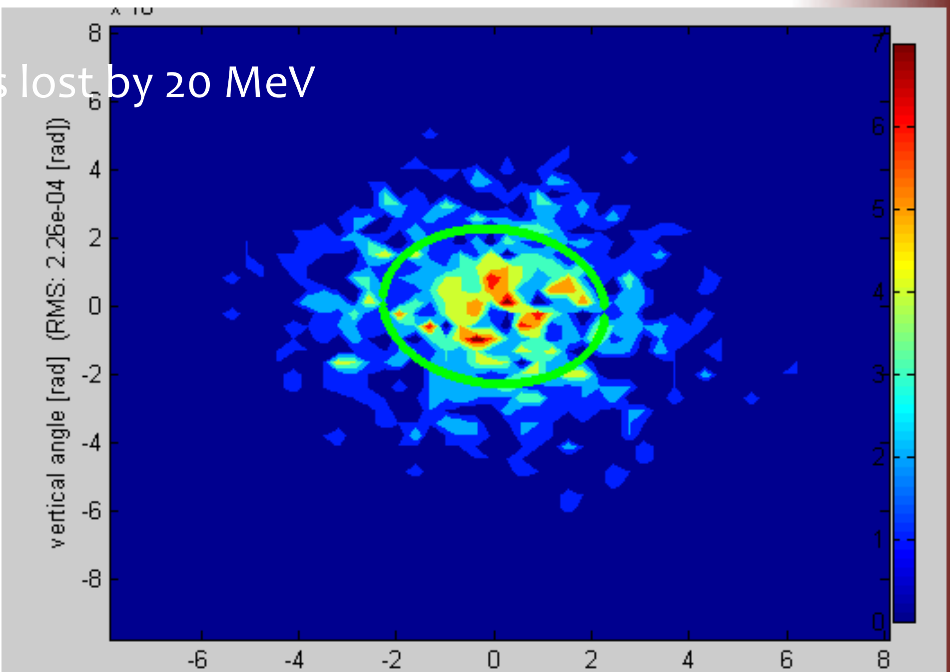
Now look at effects of synchrobetatron and space charge with 10 mA at extraction:

Move tunes near integer fraction resonances to observe growth of islands

After two turns … bunch is lost by 20 MeV



1/3 order integer effect

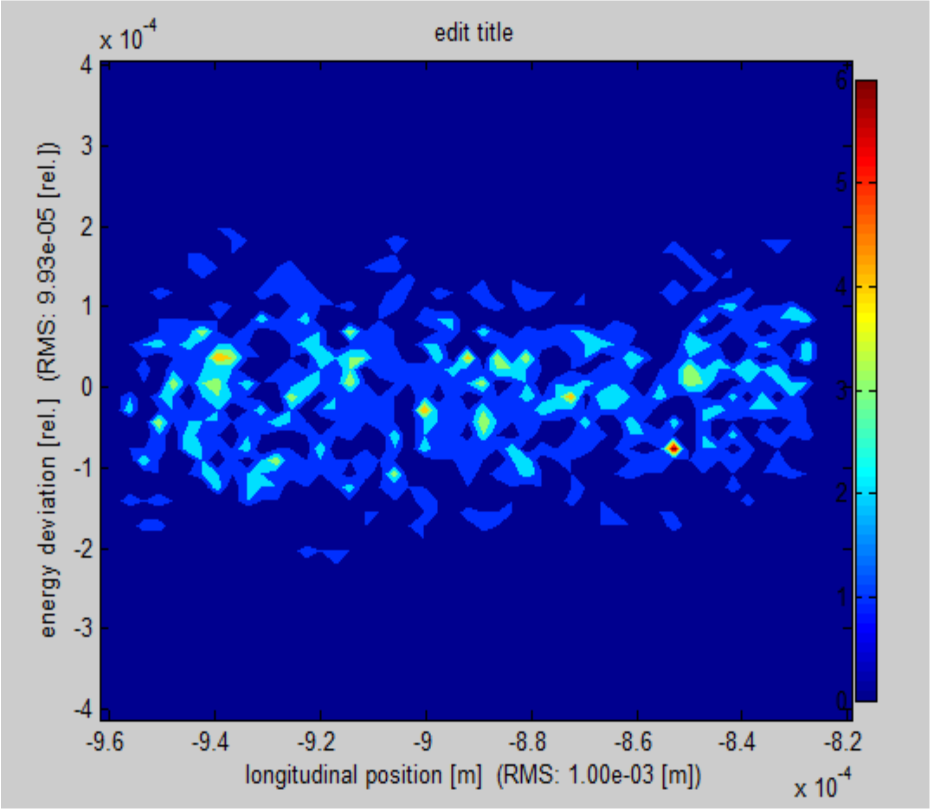


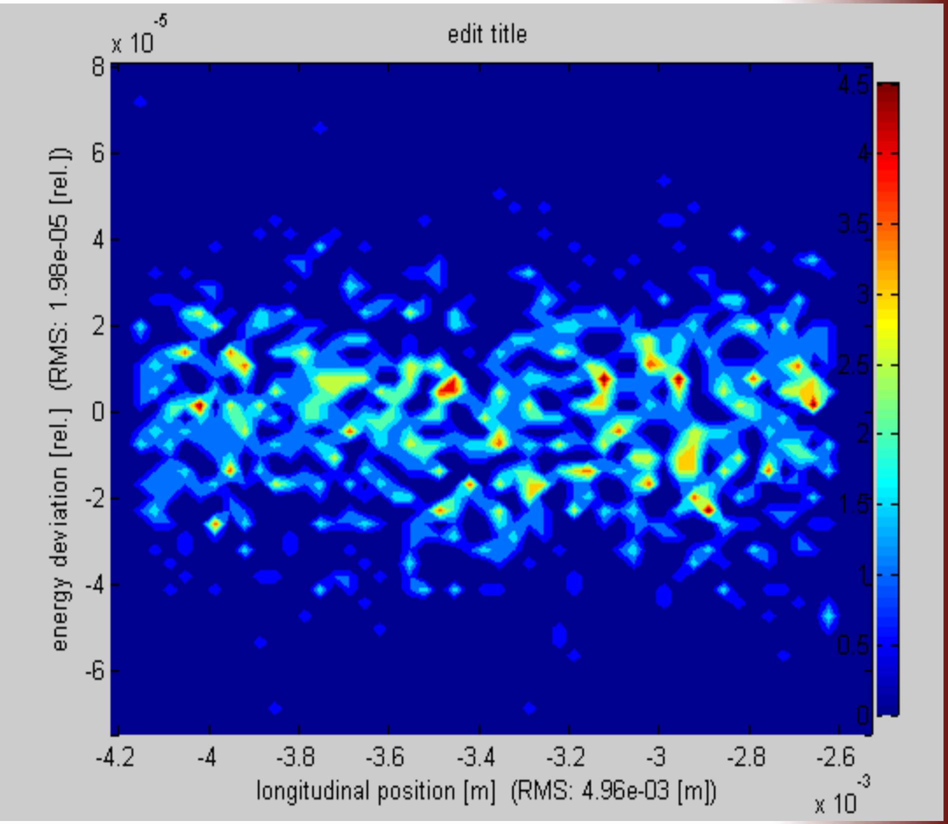
1/5 order integer effect

1/5-order islands stay clumped, 1/3-order islands are being driven. Likely driving term is edge fields of sectors (6-fold sector geometry). We are evaluating use of sextupoles at sector edges to suppress growth.

Synchrobetatron/space charge in longitudinal phase space:

Tunes again moved to approach resonances, but retaining transmission through lattice





Injection

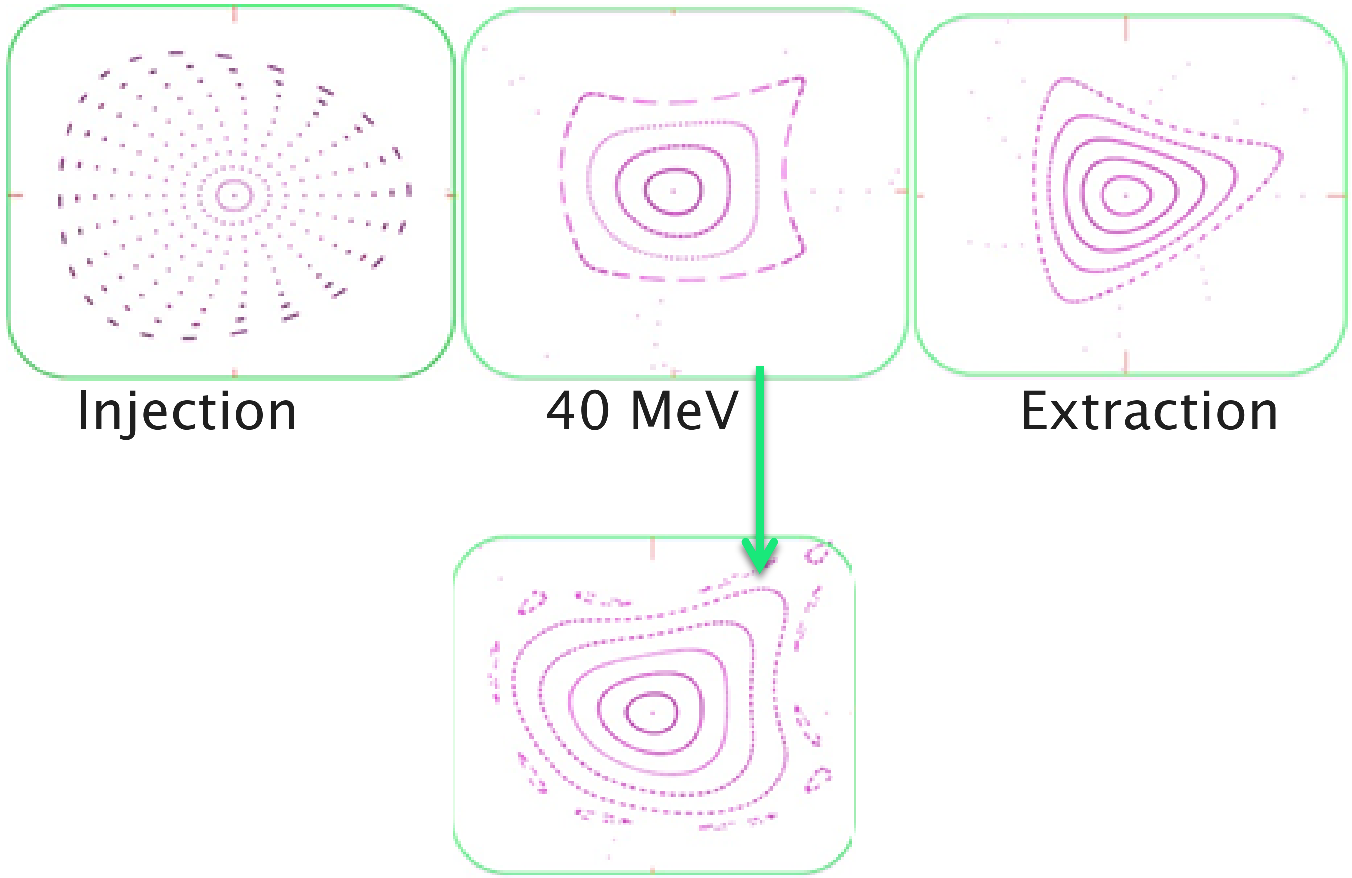
extraction

Phase width grows x5 at extraction

Poincare Plots of 5 σ contours

An example favorable operating point: $(\nu_x, \nu y) = (3.196, 3.241)$

3.5 mA beam



Now change the tune to excite a 7th order resonance

Conclusions

- The strong-focusing cyclotron is a new member of the FFAG family.
- It is optimized to accelerate the highest possible CW beam current with low losses and high energy efficiency.
- We have validated the capability of the design to accelerate 10 mA with excellent transport.
- Control of betatron tunes and ability to naturally match input RF to beam loading across the entire width of the spiral orbit are key strategic elements.
- Phase space dynamics for optimized orbit should be simple to diagnose – no COD, no E-ϕ serpentine, no resonances
- Anyone who can tune a synchrotron or linac for low loss, high current could tune a SFC.
- So far as we can determine from these early studies, it is not yet clear what will be the ultimate limits to beam current.

Future plans

To Do:

SRF cavity

- Wake fields, beam loading, optimize input coupler array
- Build/test prototype cavities

Beam Transport Channel:

- Finalize copper test wind
- Quench modeling and protection
- MgB_2 winding

Sector Magnet

- Refine pole piece and shielding fins - FEA models and prototypes

Beam dynamics

- Model beam loading, wake fields, patterns of input couples in SRF cavities

Come collaborate with us!

Thank you!